

## **Chapter 2**

### **PHYSICAL PROCESSES AND HYDROGRAPHY**

by

LGL Alaska Research Associates, Inc.  
4175 Tudor Centre Drive, Suite 101  
Anchorage, Alaska 99508

Contributions by:

J. Christopher Haney, Donald W. Hood, Susan S. Saupe, and Declan M. Troy

## TABLE OF CONTENTS

SUMMARY.....	2-3
LIST OF FIGURES.....	2-5
LIST OF TABLES.....	2-6
INTRODUCTION.....	2-7
CURRENT STATE OF KNOWLEDGE.....	2-7
Gulf of Alaska.....	2-7
Aleutian Passes and Bering Sea.....	2-9
Variability in Flow.....	2-11
Upwelling and Nutrients.....	2-12
METHODS.....	2-14
Shipboard CTD Transects.....	2-14
Remote Sensing Thermal Analyses.....	2-14
Time Series Stations.....	2-18
Nutrients and Upwelling.....	2-18
RESULTS.....	2-18
Temperature and Salinity Distributions.....	2-21
Fall 1986: CTD Transects.....	2-21
Winter 1987: CTD Transects.....	2-24
Spring 1987: CTD Transects.....	2-24
Winter 1987: Infrared Imagery.....	2-29
All Cruise Periods: Sea Surface Thermal Charts.....	2-29
CTD Casts for Tidal Effects.....	2-30
Nutrient Distributions and Upwelling.....	2-31
DISCUSSION.....	2-31
RECOMMENDED FURTHER RESEARCH.....	2-36
ACKNOWLEDGEMENTS.....	2-36
LITERATURE CITED.....	2-37
APPENDICES.....	2-39

## SUMMARY

The purpose of this study was to examine the spatial and temporal distributions of temperature, salinity, and nutrient (nitrate, nitrite) levels in the Unimak Pass area as a basis for helping to explain observed distributions of vertebrates and their prey. Distributional analyses for these water quality variables were based on shipboard CTD casts and water samples taken on transects through the area, and on inspection of remote-sensing analyses of sea surface temperatures. Shipboard sampling was conducted in fall (late September-early October), winter (late February-early March), and spring (late April-early May).

Interpretations of the collected data supported and amplified the general findings of other investigators who have studied the region's oceanography. Findings with important implications for vertebrate food webs in the area were as follows:

- (1) Four different water masses seemed to occur in the study area as a whole, based on surface salinities and mixing regimes. These were Alaska Coastal Current Water (east side of Unimak Pass adjacent to Unimak Island, surface salinity  $< 31.8$  ppt), Shelf Break Water (north and west of Unimak Pass, surface salinity  $> 32.6$  ppt), Tidally-Mixed Water (no vertical structure, occurring in shallow areas near the Krenitzin Islands), and what we called Gulf of Alaska Water (structured water of intermediate surface salinities, widely distributed in deeper, western parts of the study area).
- (2) Low-salinity Alaska Coastal Current Water was confined in all seasons to the eastern parts of Unimak Pass. Its farthest westward extension occurred in spring.
- (3) Water temperatures changed most among seasons in shallow water, particularly where Alaska Coastal Current Water prevailed. The seasonal temperature range of deep water was typically within that of shallow waters.
- (4) Reverse thermoclines were encountered in the water column in winter and spring, but were generally below the foraging depths of most seabirds. Thus, even should invertebrate or fish prey concentrate at these features, it would be of little consequence to birds.
- (5) Water quality distributional characteristics indicated that upwelling of deep Gulf of Alaska Water south of Unimak

Pass and its subsequent transport through the pass was probably an uncommon event. Rather, it seemed that upwelling probably occurred a few to several hundred km farther west in the Aleutian chain, and that this water moved eastward along the north side of the chain, eventually reaching the Unimak Pass area. This is consistent with recent findings by other workers. An area of high surface salinity, suggesting local upwelling, was present during the fall immediately northwest of Unimak Pass.

- (6) Nutrient analyses of water samples collected along transects through and parallel to Unimak Pass supported the oceanographic evidence for upwelling patterns. Nitrate/nitrite distributions indicated a source of nutrients to Unimak Pass proper that came from the north and/or west and was depleted to the east. There was local evidence of vertical mixing in the Krenitzin Islands and some other areas near Unimak Pass. Transport of deep-ocean nutrients through Unimak Pass from the south appeared unlikely.

## LIST OF FIGURES

Figure 1.	Place names and bathymetry in the Unimak Pass area, Alaska.....	2-8
Figure 2.	Schematic representation of the major currents in the Gulf of Alaska .....	2-10
Figure 3.	Locations of CTD stations sampled during the fall 1987 cruise.....	2-15
Figure 4.	Locations of CTD stations sampled during late winter 1987 cruise.....	2-16
Figure 5.	Locations of CTD stations sampled during the spring 1987 cruise.....	2-17
Figure 6.	Transect for nitrites/nitrates in the Unimak Pass area, Alaska.....	2-20
Figure 7.	Surface temperatures ( $^{\circ}\text{C}$ ) in the Unimak Pass study area during the fall cruise (MF-86-10).....	2-22
Figure 8.	Surface salinities (ppt) in the Unimak Pass study area during the fall cruise (MF-86-10).....	2-23
Figure 9.	Surface temperatures ( $^{\circ}\text{C}$ ) in the Unimak Pass study area during the winter cruise (MF-87-02).....	2-25
Figure 10.	Surface salinities (ppt) in the Unimak Pass study area during the winter cruise (MF-87-02).....	2-26
Figure 11.	Surface temperatures ( $^{\circ}\text{C}$ ) in the Unimak Pass study area during the spring cruise (MF-87-05).....	2-27
Figure 12.	Surface salinities (ppt) in the Unimak Pass study area during the spring cruise (MF-87-05).....	2-28
Figure 13.	Isolines of nitrate (in $\mu\text{M}$ ) on the north Aleutian Shelf during March 1987.....	2-32
Figure 14.	Isolines of nitrate (in $\mu\text{M}$ ) through Unimak Pass during September 1986.....	2-32
Figure 15.	Isolines of nitrate (in $\mu\text{M}$ ) through Unimak Pass during February 1987.....	2-33

Figure 16. Principal water masses in the Unimak Pass study area..... 2-35

### LIST OF TABLES

Table 1.	Times, depths, and positions for time-series casts at Station 26.2 in Unalga Pass.....	2-19
Table 2.	Times, depths, and positions for time-series casts at Stations 21.3 in Akutan Pass.....	2-19
Table 3.	Times, depths, and positions for time-series casts at Station 6.4 in the east side of Unimak Pass .....	2-19
Table 4.	Times, depths, and positions for time-series casts at Station 21.1 north of Unalaska Island.....	2-19

## INTRODUCTION

A major objective of the Unimak Pass study was to relate the seasonal distributions, abundances, and activities of marine birds and mammals to oceanographic features and processes. This section helps to address this objective by examining the spatial and temporal distributions of temperature, salinity, and nutrients in waters of the study area.

Unimak Pass (Fig. 1) is the shallowest and easternmost of the passes situated in the eastern Aleutian Islands. The pass is approximately 18 km wide at its narrowest point and generally is less than 100 m deep; this is relatively shallow in comparison with major passes farther west in the Aleutian chain.

The study area encompassed Unimak Pass and adjacent waters within about 50 km of the pass. Included are the western half of Unimak Island and the northeastern tip of Unalaska Island. Passes, straits, and islands included are Akutan (including Baby) and Unalga passes; Ugamak, Derbin, Avatanak, Rootok, and Akun straits; and Ugamak, Tigalda, Avatanak, Akun, Rootok, Akutan, Unalga, and the Baby islands.

Areas within 10 km of land and in the narrow straits between islands are generally less than 60 m deep. Several shallow banks lie within Unimak Pass and at the western end of Unimak Island. The southeastern portion of the study area includes part of Davidson Bank, where the northern Gulf of Alaska continental shelf is relatively wide and depths are less than 100 m. Southernmost reaches of the study area approach the continental shelf break (1000 m deep). Northeasternmost stations are in Bering Sea continental shelf waters; some of the northwestern stations are on the Bering continental slope.

## CURRENT STATE OF KNOWLEDGE

What was known prior to the present study about the circulation and water chemistry in Unimak Pass and vicinity is summarized in this section. For two reasons, studies conducted in adjacent regions are the major sources of information. First, previous to this study little work had been done in Unimak Pass proper. Second, processes taking place in nearby areas strongly influence circulation and resultant water quality in Unimak Pass. The following discussion is excerpted largely from Hood (1986).

### Gulf of Alaska

In the northern Gulf of Alaska, the predominantly westward-flowing water masses transfer water into the Bering Sea through the Aleutian passes

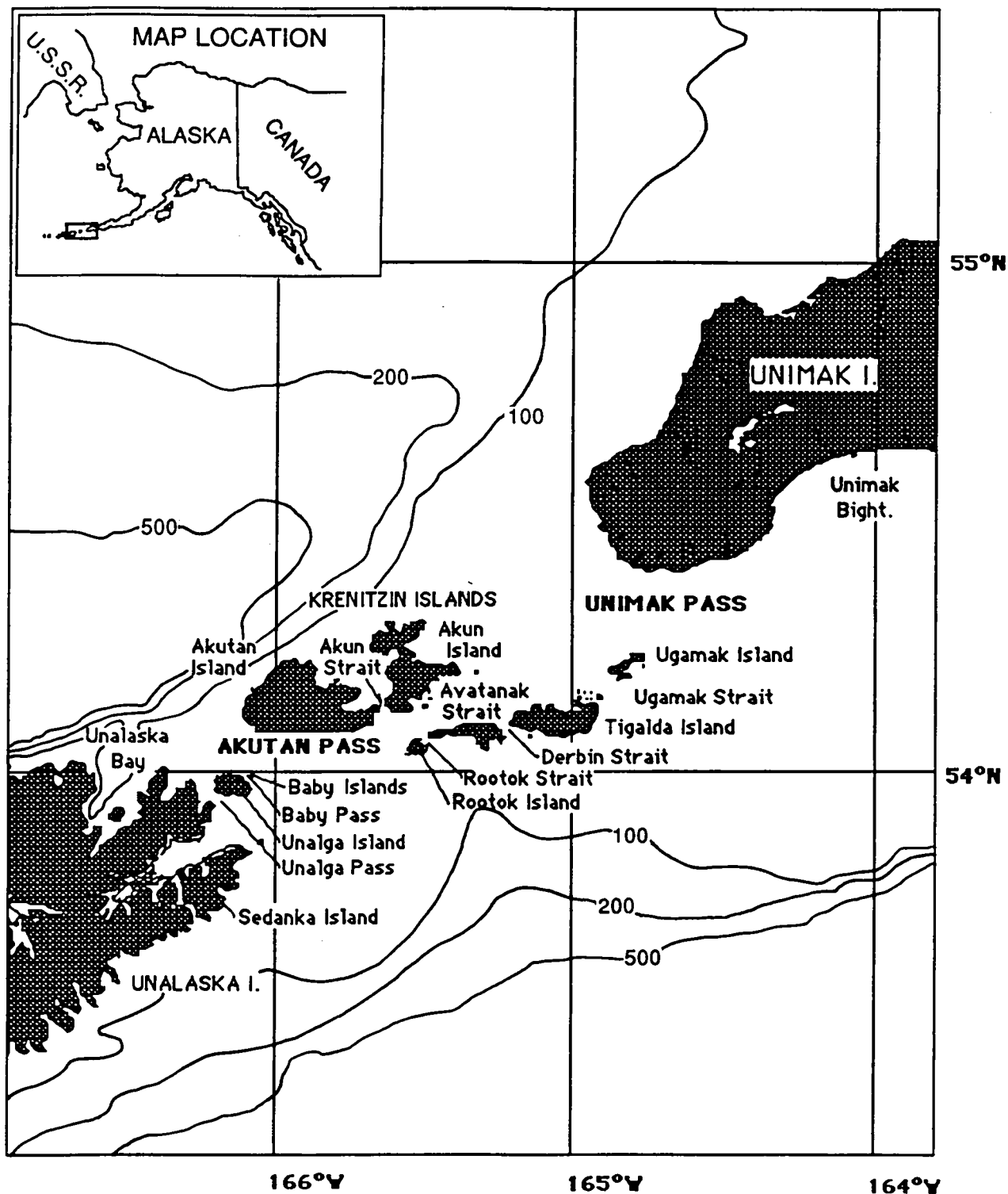


Figure 1. Place names and bathymetry (m) in the Unimak Pass area, Alaska.

(Fig. 2). The major currents that influence flow in the vicinity of Unimak Pass are the Alaska Coastal Current and the Alaska Stream (Hood 1986).

The Alaska Coastal Current (also called the Kenai current in the northern Gulf of Alaska) is a coastal flow that originates in the eastern Gulf of Alaska along the shores of British Columbia and follows the coast first northward to the northern Gulf and then southwest to Unimak Pass (Schumacher and Reed 1980, Schumacher et al. 1982). The speed of this current is between 10 and 20 cm/s throughout its length, except near the Kenai Peninsula where it intensifies to as much as 100 cm/s.

The Alaska Stream parallels and is adjacent to the Coastal Current, but is off the shelf. It moves in the same general direction at (usually) higher speeds. It is formed in the eastern Gulf of Alaska as a result of the bifurcation of the Subarctic Current, which is the eastern and poleward boundary of the large, counterclockwise Subarctic Gyre.

Upstream from Unimak Pass, the Coastal Current waters near the coast may have salinities as low as 26 ppt due to freshwater discharges. (These discharges may actually drive the Alaska Coastal Current.) But as the Coastal Current waters move westward toward Unimak Pass, river input becomes much less and salinities moderate to 31 or 32 ppt in the vicinity of the pass. (Salinities in Alaska Stream surface waters south of the pass approach 33 ppt.)

Temperatures in the Coastal Current waters are more variable seasonally than those in the deeper Alaska Stream water. In the vicinity of Unimak Pass, surface temperatures of shelf waters may range from slightly above 0° C in winter to as high as 10° C in some areas in summer (Craig 1987). Temperatures of Alaska Stream water in winter range from <3° C to > 5° C, depending on depth; summer temperatures near the surface are a few degrees higher.

### **Aleutian Passes and Bering Sea**

Historically, there have been numerous attempts to determine which Aleutian Chain passes accommodate the flows of various water masses that move from the northern Gulf of Alaska into the Bering Sea (Hood 1986). In this study the concern was mainly with the water masses making important contributions to waters in the Unimak Pass area.

Schumacher et al. (1982) summarized the available data on exchange of water through Unimak Pass and concluded that most of the Alaska Coastal Current moved through the pass. Water of salinity less than 31.75 ppt, which these authors defined as Alaska Coastal Current water, dominates the surface regime on the eastern side of the pass, and currents in the pass tend to follow the isobaths. Waters with such low salinities are not found west of Unimak Pass along the Aleutian Chain.

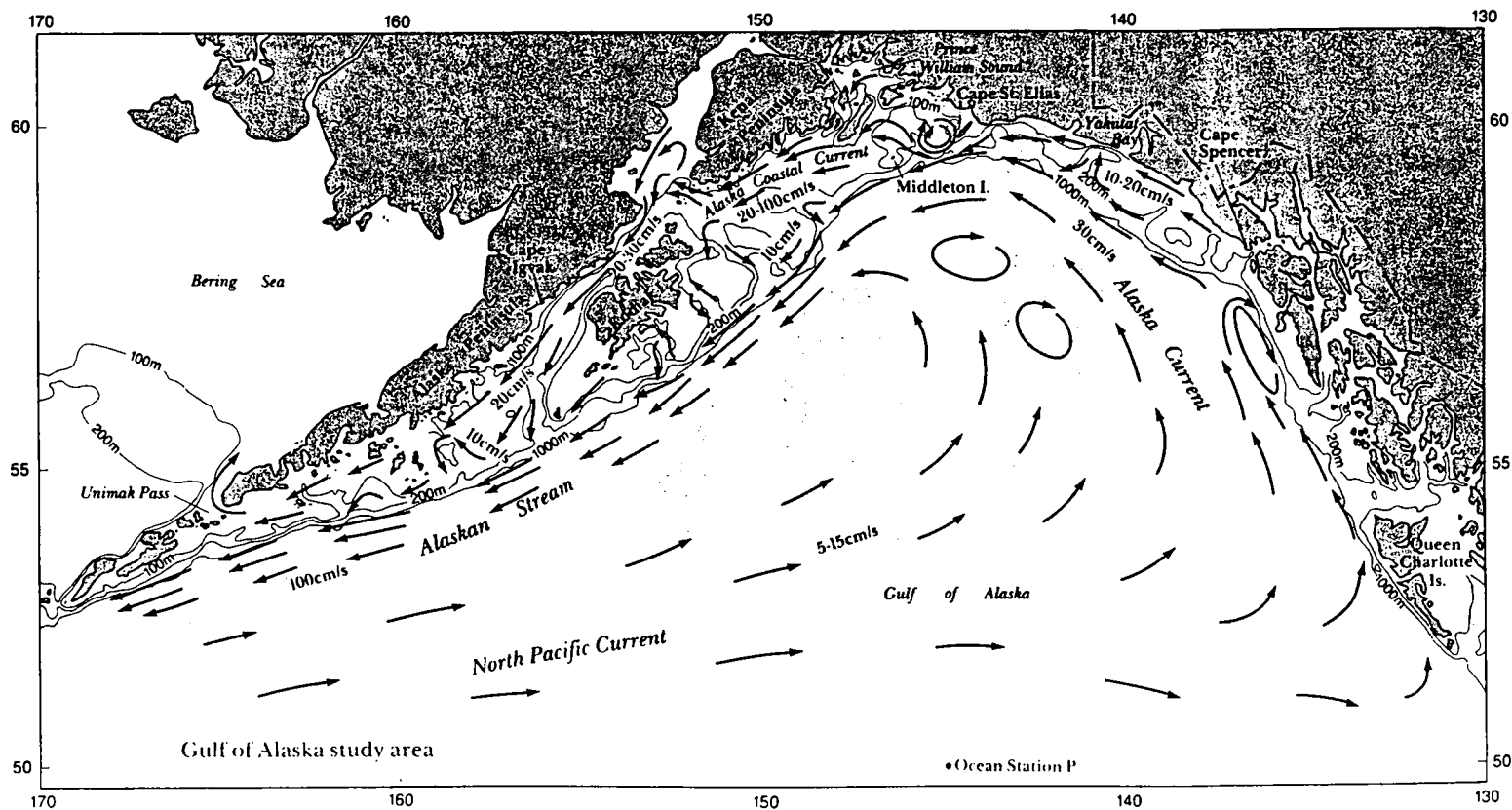


Figure 2. Schematic representation of the major currents in the Gulf of Alaska (from Reed and Schumaker 1986).

More recently, Nof and Im (1985), using theoretical modeling of suction through broad ocean passes, provided interpretations supporting this idea. Their model predicted that a separated boundary current encountering a broad gap on its righthand side is sucked in its entirety into the adjacent basin; such a current flowing along a wall with a series of broad gaps (similar to the situation in the eastern Aleutian chain) will enter only the first gap. When they applied the model to Unimak Pass, it showed the Alaska Coastal Current flowing through the pass and then moving northeast along the Bering Sea side of the Alaska Peninsula. An analysis of the relevant salinity data available for the period 1929-1974 (a total of 1342 stations) revealed that water with similarly low salinity appeared on both sides of the Alaska Peninsula east of Unimak Pass but not west of the pass, thus supporting the model.

In contrast, waters of the offshore Alaska Stream do not appear to penetrate the easternmost Aleutian passes, but instead flow into the Bering Sea through passes farther to the west. Near Strait, near the western end of the Aleutian Chain, seems to accommodate much of this water (Hughes et al. 1974, Favorite 1974).

The presently accepted scheme of surface circulation in the Bering Sea adjacent to the Aleutian chain shows a current flowing from at least the central portion of the chain eastward to Unimak Pass. Takenouti and Ohtani (1974) identified Alaska Stream type water along the north side of the Aleutian Islands, including the area immediately north of Unimak Pass. This water has homogeneous temperatures between 4° and 5° C down to 100-m depths, and homogeneous salinities to the same depths. The major component of this current seems to turn northward to form the Shelf Break Current upon reaching the shelf break just north of the pass (Kinder and Schumacher 1981).

### Variability in Flow

The passage of low-pressure storm systems along the Aleutian storm track strongly influences the water quality as well as the strength and direction of water flow in the Unimak Pass area. The intensity of storms is greatest in the winter months, October through April, during which an average of one storm every four or five days crosses the Bering Sea and the Gulf of Alaska, generally from west to east.

These storms bring strong winds, nearly continuous cloud cover, and warm, moist air ahead of cold fronts. The moisture is intercepted by high mountain ranges in the coastal areas of the Gulf of Alaska, generating runoff that dilutes Alaska Coastal Current water, ultimately affecting water salinity in the Unimak Pass area.

The direction of the wind field during these storms strongly influences the differences in water levels across Unimak Pass, and consequently the direction and magnitude of flow through the pass. The passage of a low across the Aleutians in the vicinity of Unimak Pass tends to increase the flow into the Bering Sea as the front moves through, due to the easterly and southerly winds. The dominant storm winds tend to be easterly, and under these winds the surface waters south of the Alaska Peninsula tend to converge on the coast, causing down-welling. On the Bering Sea side, the coastal waters tend to diverge, causing upwelling. As the storm passes, the flow relaxes and reverses its direction.

During summer the low-pressure systems are weaker and tend to migrate farther north. A high-pressure system is established over the Gulf of Alaska, causing a periodic shift in wind patterns from easterly to westerly with consequent coastal divergence of water and limited upwelling south of the Alaska Peninsula.

Though flows through Unimak Pass from the Gulf of Alaska into the Bering Sea periodically reverse, as described above, Schumacher et al. (1982) found reversals to occur in only 18% of the spring and 31% of the summer observations. Mean flow was three times greater in spring than in summer.

### **Upwelling and Nutrients**

In 1966, Dugdale and Goering (1967) observed a high nutrient content in waters near Unimak Pass and suggested that it was caused by deeper Pacific Ocean water passing over the shallow sill of Unimak Pass and effecting vertical transport, a form of upwelling. Subsequently, Kelley et al. (1971) measured the partial pressure of CO<sub>2</sub> in the surface waters of sites in the eastern Aleutians to detect and map areas of upwelling.

The CO<sub>2</sub> technique for detecting and measuring upwelling is based on changes in the levels of carbon dioxide in the water as it rises to the surface. Near the sea surface, use of CO<sub>2</sub> by phytoplankton during periods of primary productivity (and by animals in the formation of calcareous shells) lowers the partial pressure of CO<sub>2</sub> below that of the overlying air mass. Recycling of organic carbon and dissolution of calcium carbonate in the water column release CO<sub>2</sub>; this occurs at all depths in the water column and increases the CO<sub>2</sub> values. Thus, below the euphotic zone, where photosynthesis does not occur, the CO<sub>2</sub> produced by recycling accumulates, and if these deeper waters are brought to the surface, they are supersaturated in CO<sub>2</sub> with respect to the atmosphere.

Because of the very large difference in CO<sub>2</sub> levels between surface waters (values as low as 125 microatmospheres) and deeper waters (values as high as 600 microatmospheres), measurement of the surface value of CO<sub>2</sub> is

probably the most sensitive method available for mapping upwelling in high latitudes. The conventional method of mapping sea surface temperatures is less useful at higher latitudes than in more temperate areas because there is a small vertical range of temperatures and upwelled water is not always colder than the adjacent surface waters.

Kelley et al. (1971) used the CO<sub>2</sub> technique to map upwelling along the eastern Aleutian Islands. During June and September, these authors found Unimak Pass waters to be undersaturated in CO<sub>2</sub> with respect to the atmosphere, in contrast to high supersaturated values at the deeper Samalga and Amukta passes some 300-400 km to the west. The high values in the west were interpreted as resulting from the upwelling of deep Gulf of Alaska water as it flowed through Samalga and Amukta passes; the low values at Unimak Pass were interpreted to be caused by primary productivity having stripped CO<sub>2</sub> from the surface waters. The waters at Unimak Pass could well have been originally upwelled farther west in Aleutian passes; if this was the case, it could easily have lost its CO<sub>2</sub> to phytoplankton as it moved eastward in the euphotic zone.

Additional studies in the eastern Aleutians (Kelley and Hood 1974, Hood and Kelley 1976) disclosed high CO<sub>2</sub> levels in surface waters near Unimak Pass indicating that water had been brought from depth in the Krenitzin Islands-Unimak Pass area as well as in the Samalga Pass area. The values near Samalga Pass were so large that the authors believed them to have certainly been caused by upwelling from 150- 200-m depths; those near Unimak Pass were smaller and were interpreted to have been the result of tidal mixing.

Although physical and biological clues support the idea of a nutrient-enriched area in the vicinity of Unimak Pass, nutrient analyses in the area have been limited. Koike et al. (1979, 1982) occupied sampling stations along a transect through the pass on 30 July 1978. They found chlorophyll-a and nitrate concentration patterns not inconsistent with the idea of upwelling along the Aleutian Chain west of Unimak Pass. Off the shelf immediately northwest of Unimak Pass, chlorophyll-a concentrations were high and nitrate concentrations were low, both suggesting a high level of primary productivity (Koike et al. 1982). In the southeastern (narrowest) part of Unimak Pass and east of the pass south of the Alaska Peninsula (possibly located within the Alaska Coastal water moving through the pass), chlorophyll-a concentrations were lower and nitrate concentrations higher.

## METHODS

### Shipboard CTD Transects

Hydrographic (CTD) stations in the Unimak Pass study area were occupied on three cruises of the R/V Miller Freeman: 18 September - 7 October 1986 (Fig. 3), 14 February - 9 March 1987 (Fig. 4), and 21 April - 14 May 1987 (Fig. 5). A total of 254 stations was sampled during the three cruises. Summaries of station locations, dates, casts, and times of day are given in Appendices A-C.

A model 9040/9041 Plessey/Grundy CTD system was used to record and calculate water temperature, salinity, density ( $\sigma_t$ ), and geopotential anomaly ( $\partial d$ ) for each meter of the cast. The values recorded by the CTD were checked against salinity samples obtained from rosette-mounted 5-L Niskin bottles and temperatures obtained from deep-sea reversing thermometers mounted on these bottles. Station depths ranged from 40 to 2195 m, but actual cast depth seldom exceeded 800 m.

The CTD data tape, and calibration and quality control information, were sent to the Institute of Marine Science, University of Alaska, Fairbanks, for reduction. The resulting product was a tabulation, suitable for analyses on personal computers, that listed temperature, salinity,  $\sigma_t$ , and geopotential anomaly averaged over 1-m intervals.

These reduced data were then presented as vertical profile plots for each of the four water quality variables. Surface hydrographic data for the entire study area collected during a cruise were presented as horizontal contour plots of temperature and salinity. These vertical and horizontal plots were then used as a basis for characterizing water masses.

### Remote Sensing Thermal Analyses

Horizontal distributions of sea-surface temperatures were also evaluated on the basis of remote sensing information. Satellite images showing surface temperature distributions in the vicinity of Unimak Pass were obtained from the Gilmore Creek NASA Tracking Station in Fairbanks. Photographic images were based on the 4Z and 94Z infrared enhancement curves and covered the period 25 February - 6 March 1987. For some days when cloud cover was minimal, up to two images were available.

Cartographic presentations of sea-surface temperature were available from NOAA/NWS Sea Surface Thermal Analysis charts. These charts present horizontal contours of temperature for the northern Gulf of Alaska

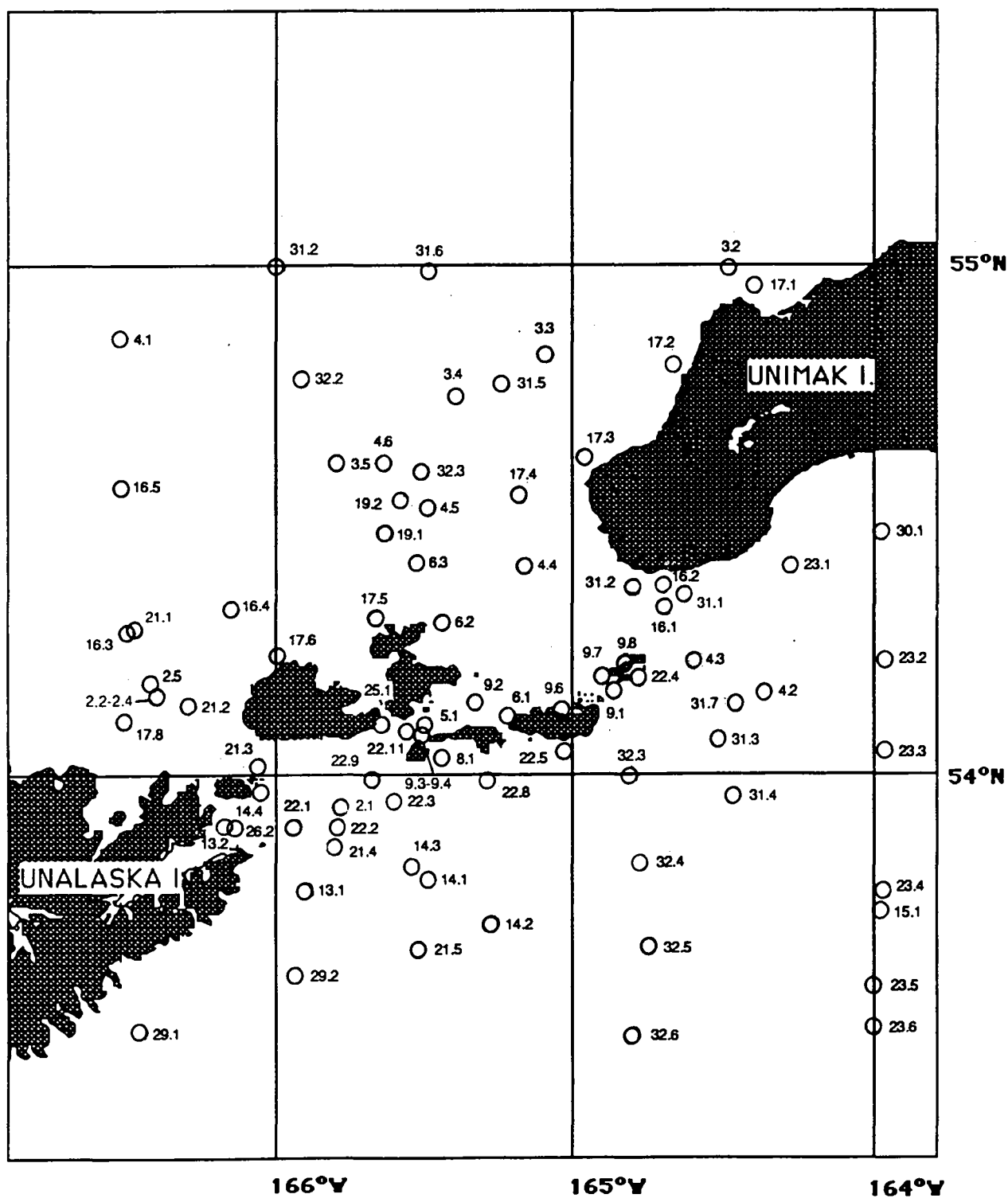


Figure 3. Locations of CTD stations sampled during the fall 1986 cruise, 18 Sept-7 Oct, in the Unimak Pass area, Alaska.

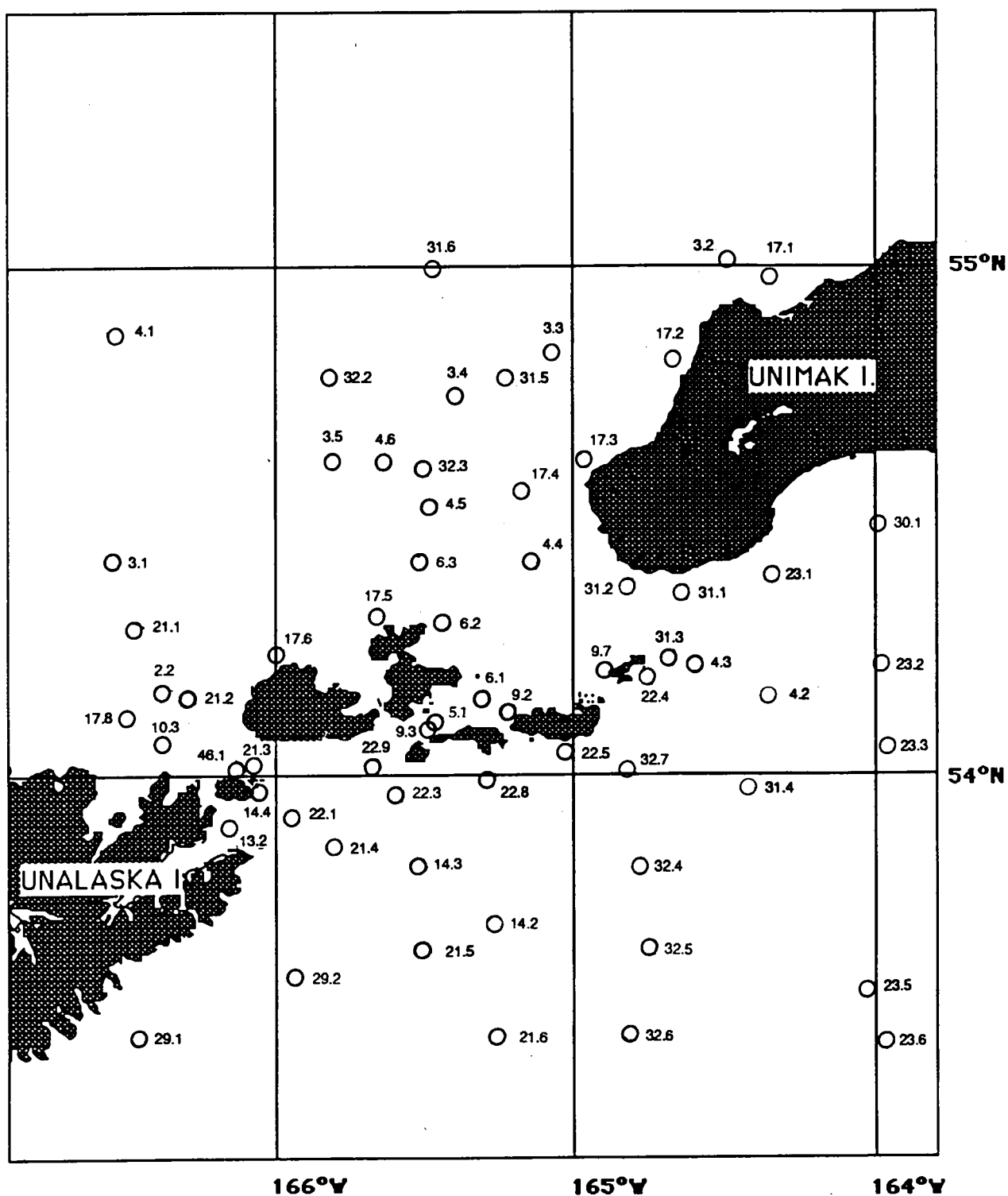


Figure 4. Locations of CTD stations sampled during the winter 1987 cruise, 14 Feb-9 March, in the Unimak Pass area, Alaska.

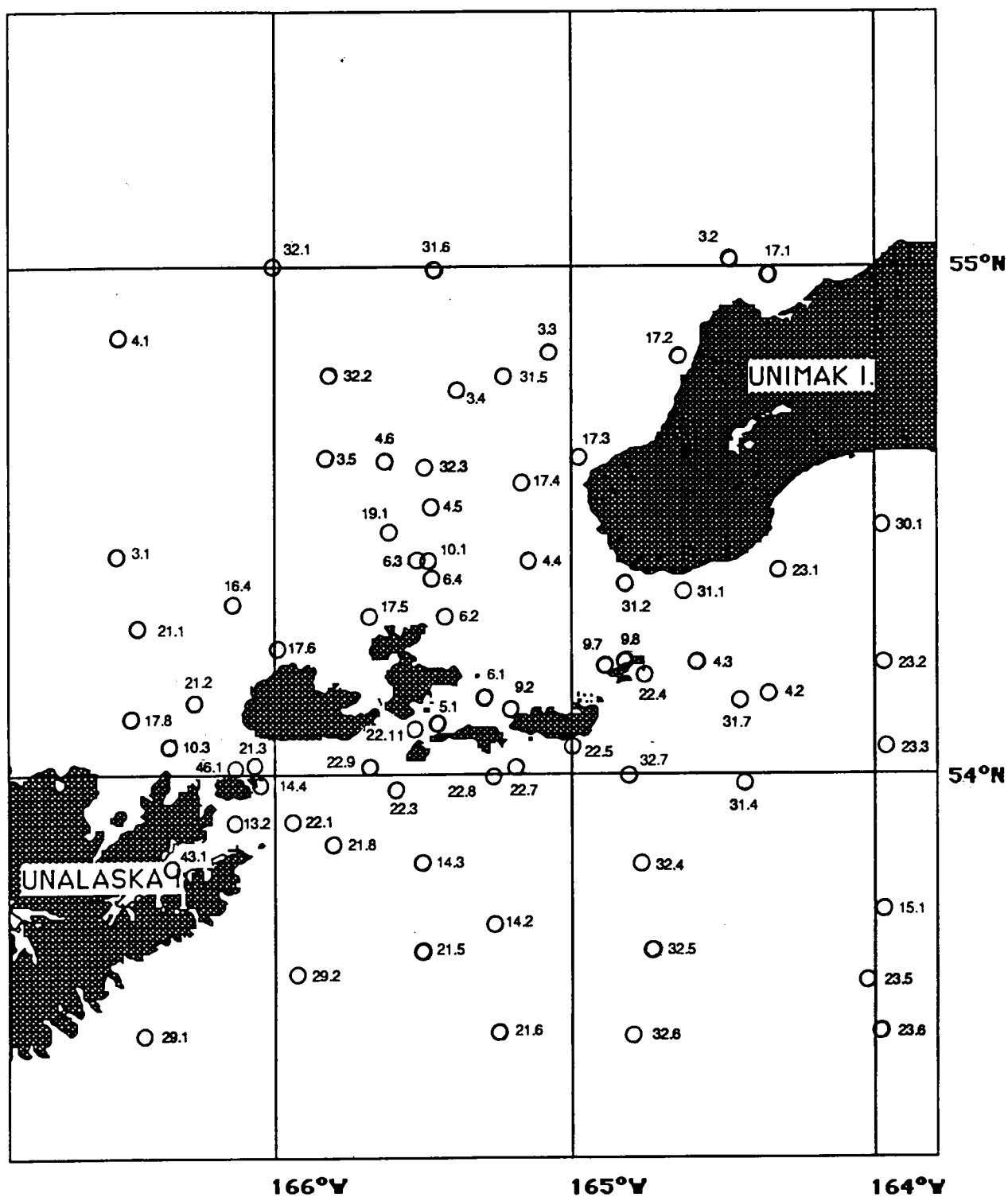


Figure 5. Locations of CTD stations sampled during the spring 1987 cruise, 21 April-14 May, in the Unimak Pass area, Alaska.

and Bering Sea at relatively coarse scales. Charts covered the entire period of each cruise, and generally several days or weeks on either end of the cruise.

### Time Series Stations

Four stations were sampled repeatedly (approximately every two hours) for changes in water mass properties due to tidal fluctuations. Station 26.2 (330 m) at the mouth of Beaver Inlet was sampled seven times on 7 October 1986 (Table 1). Station 21.3 (70 m) in Akutan Pass north of the Baby Islands was sampled six times between 2000 hrs AST on 6 March and 0600 hrs AST on 7 March 1987 (Table 2). Station 6.4 (100 m) at the eastern edge of Unimak Pass near Akun Island was sampled six times between 2100 hrs ADT on 7 May and 0700 hrs ADT on 8 May 1987 (Table 3). Station 21.1 (1040 m), approximately 30 km north of Unalaska Bay, was sampled five times on 11 May 1987 (Table 4).

### Nutrients and Upwelling

Measurements of the vertical and horizontal distributions of nitrate/nitrite were made using water samples collected along three transects near Unimak Pass (Fig. 6). An along-shelf transect (Stations 3.1-3.5) was conducted north of Unimak Pass. Two transects were conducted through study area passes: Transect 21 (Stations 21.1-21.5) ran through Akutan Pass and Transect 4 (Stations 23.3 and 4.2-4.6) ran through Unimak Pass.

Water samples were collected from the water column at various depths at stations along transects. These samples were immediately frozen in 250 ml bottles. At the University of Alaska in Fairbanks, analyses for nitrate/nitrite and ammonia were carried out using standard methods (Strickland and Parsons 1972) adapted to a Technicon Autoanalyzer.

## RESULTS

Water temperature, salinity, and nutrient distributions in the Unimak Pass area as measured during the 1986 and 1987 cruises of the R/V Miller Freeman are presented in the following subsections. Surface distributions of properties are shown; these help characterize water mass habitats for surface-feeding seabirds. The locations of strong pycnoclines, where prey of diving seabirds could be concentrated, are also described. Apparent tidal effects on oceanographic properties in the study area are presented. Vertical and horizontal distributions of nitrates, and what this implies about characteristics of upwelling in the Unimak Pass area, are identified.

Table 1. Times, depths, and positions for Station 26.2 time-series casts at the mouth of Beaver Inlet in Unalga Pass, Unimak Pass area, Alaska.

Station	Date	Time (ADT)	Depth (m)	Latitude (°N)	Longitude (°W)
26.2a	07-Oct-1986	05:20	305	53.9023	166.1058
26.2b	07-Oct-1986	07:11	310	53.9027	166.1150
26.2c	07-Oct-1986	09:13	312	53.9018	166.1035
26.2d	07-Oct-1986	11:13	320	53.9017	166.1277
26.2e	07-Oct-1986	13:12	329	53.9012	166.1255
26.2f	07-Oct-1986	15:03	330	53.9070	166.1295
26.2g	07-Oct-1986	17:08	241	53.8940	166.1058

Table 2. Time, depths, and positions for Station 21.3 time-series casts in Akutan Pass north of the Baby Islands, Unimak Pass area, Alaska.

Station	Date	Time (AST)	Depth (m)	Latitude (°N)	Longitude (°W)
21.3a	06-Mar-1987	20:21	43	54.0237	166.0613
21.3b	06-Mar-1987	22:01	48	54.0247	166.0448
21.3c	07-Mar-1987	00:08	63	54.0258	166.0737
21.3d	07-Mar-1987	02:07	53	54.0213	166.0647
21.3e	07-Mar-1987	04:03	44	54.0218	166.0742
21.3f	07-Mar-1987	06:04	71	54.0273	166.0877

Table 3. Time, depths, and positions for Station 6.4 time-series casts north of Akun Island on the east side of Unimak Pass, Alaska.

Station	Date	Time (ADT)	Depth (m)	Latitude (°N)	Longitude (°W)
6.4a	07-May-1987	21:02	102	54.3900	165.4890
6.4b	07-May-1987	22:57	98	54.3912	165.4920
6.4c	08-May-1987	01:00	97	54.3897	165.4967
6.4d	08-May-1987	03:00	97	54.3895	165.4962
6.4e	08-May-1987	05:02	102	54.3912	165.4893
6.4f	08-May-1987	07:18	102	54.3918	165.4893

Table 4. Times, depths, and positions for Station 21.1 time-series casts north of Unalaska Bay, Unalaska Island, Alaska.

Station	Date	Time (ADT)	Depth (m)	Latitude (°N)	Longitude (°W)
21.1a	11-May-1987	04:09	975	54.2985	166.4590
21.1b	11-May-1987	06:08	1040	54.2950	166.4548
21.1c	11-May-1987	20:07	1017	54.2970	166.4617
21.1d	11-May-1987	22:34	1024	54.2965	166.4587
21.1e	12-May-1987	00:05	1016	54.2962	166.4627

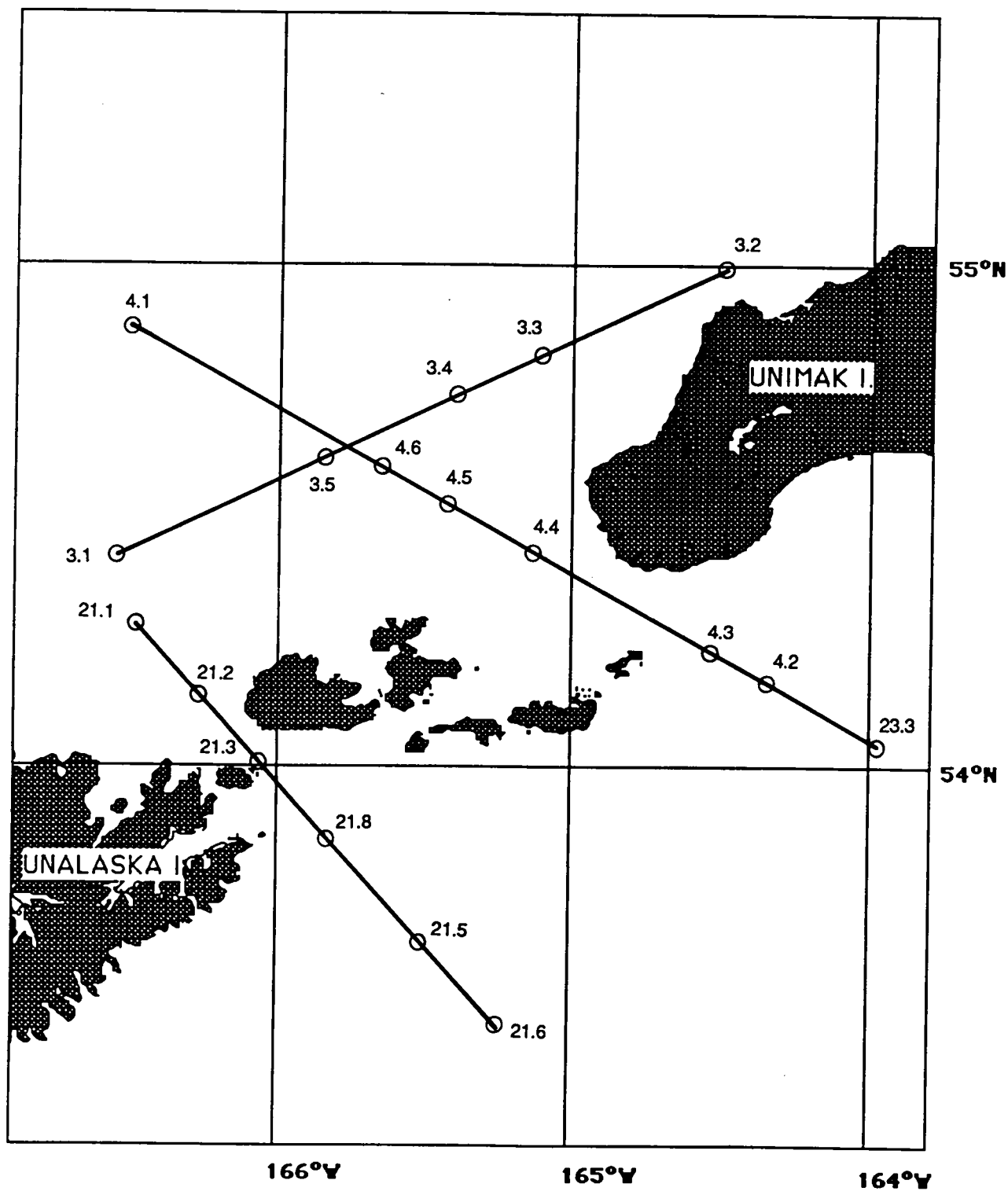


Figure 6. Transects along which nitrate and nitrite measurements were made, Unimak Pass, Alaska. Station numbers are indicated.

## Temperature and Salinity Distributions

Distributions of temperature and salinity in fall, winter, and spring, as measured by shipboard CTD sampling and remote sensing (temperature), are presented in this section. CTD results shown represent summaries based on analyses of data acquired at sampling stations; these data are shown in greater detail in Chapter 10. APPENDICES at the end of this volume.

### Fall 1986 : CTD Transects

Horizontal differences in study area sea surface temperatures were larger ( $6.7\text{--}11^\circ\text{C}$ ) during the fall cruise period than in winter or spring. During fall, the warmest water occurred in the southeastern corner of the study area near the edge of the Gulf of Alaska continental shelf (Fig. 7). The coolest water was found surrounding Akutan and Akun islands in the central portion of the study area. A warm body of water east of Unalaska Island, which also corresponded with relatively saline water (see below), may have indicated the presence of a warm oceanic eddy in the eastern portion of the study area.

Surface salinities ranged from 31.5–32.8 ppt during the fall and were lowest immediately adjacent to Unimak Island (Fig. 8). Following the suggestion of Hood (1986) that water of salinity less than about 31.8 ppt represents Alaska Coastal Water, we see that this water mass maintained its identity through the pass on the east side of the pass and around to the northeast of Unimak Island (cf Fig. 8; Schumacher et al. 1982). A saline body of water that occurred east of Unalaska Island corresponded with the area of a proposed eddy discussed above. The most saline water was found northwest of Unimak Pass over the continental slope of the Bering Sea.

Vertically well-mixed waters were encountered at Avatanak Strait (Station 6.1), Ugamak Strait, north of Ugamak Island (Station 9.7), in Unalga Pass at the mouth of Beaver Inlet (Station 13.2), at Baby Pass (Station 14.4), at Akutan Pass (Station 21.3), at the south side of Akun Strait (Station 25.1), and south of Akutan Island (Station 26.2) (Chapter 10: Appendix B-1, this volume). Water depths at these locations were shallow, ranging from 35 to 82 m, except for Station 26.2 which had a depth of 300 m. Surface-to-bottom temperature and salinity gradients at these well-mixed stations varied by only  $0.01\text{--}0.11^\circ\text{C}$  and 0.01–0.06 ppt, respectively.

During this cruise, stratified waters occurred over deep water, mainly at distances greater than 25 km from the nearest land mass (Chapter 10: Appendix A, B-1; this volume). For 22 stations that exhibited a high degree of stratification, mean vertical temperature gradients were  $3.7^\circ\text{C}$  and average thermocline thickness was 24.5 m. Three highly stratified stations occurred near land: Station 30.1 in Unimak Bight, Station 31.3 northeast of Ugamak Island in Unimak Pass, and Station 31.7 southeast of Ugamak Island.

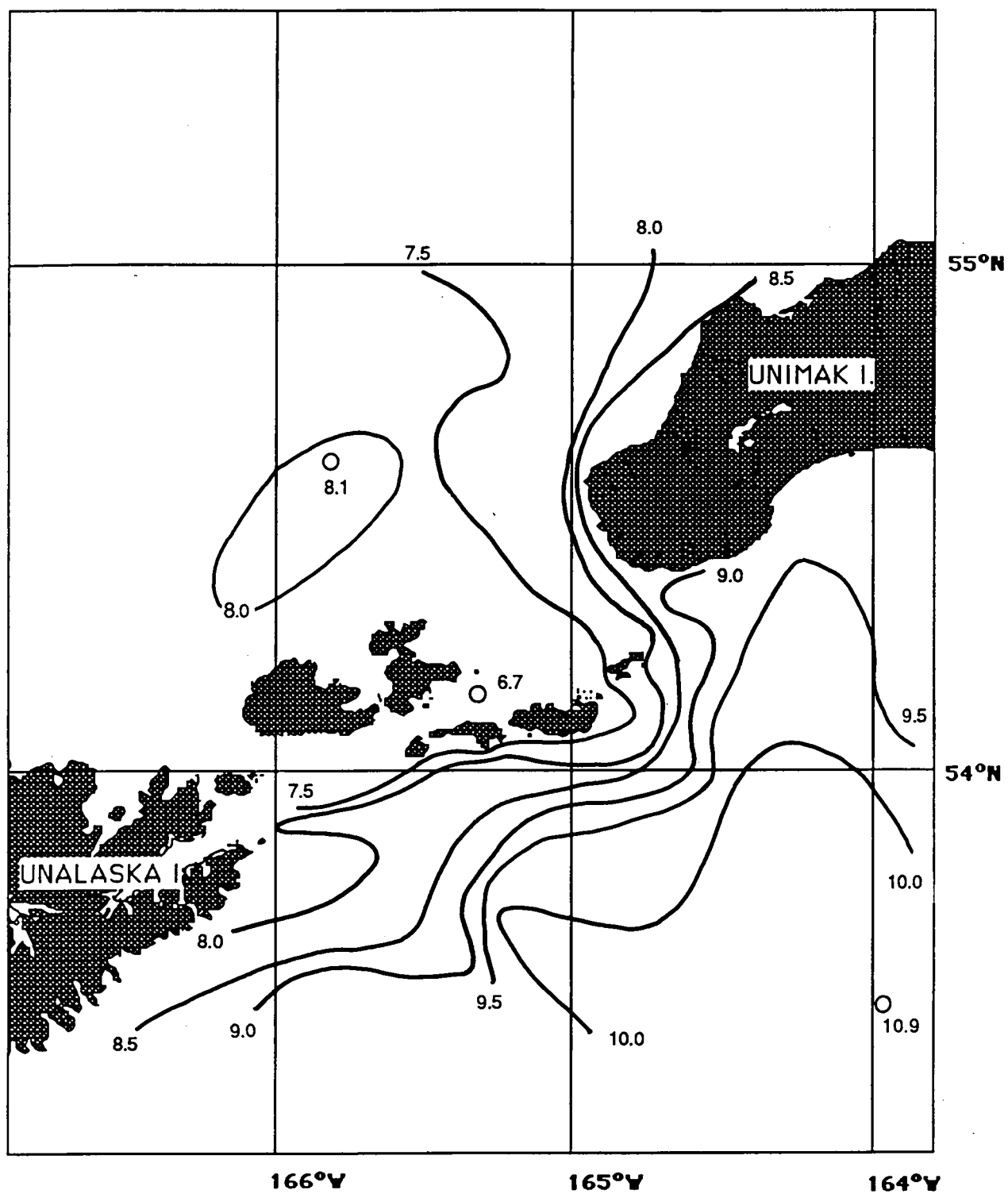


Figure 7. Sea surface temperatures (degrees C) in the Unimak Pass area, Alaska during the fall cruise, 18 Sept-7 Oct, 1986.

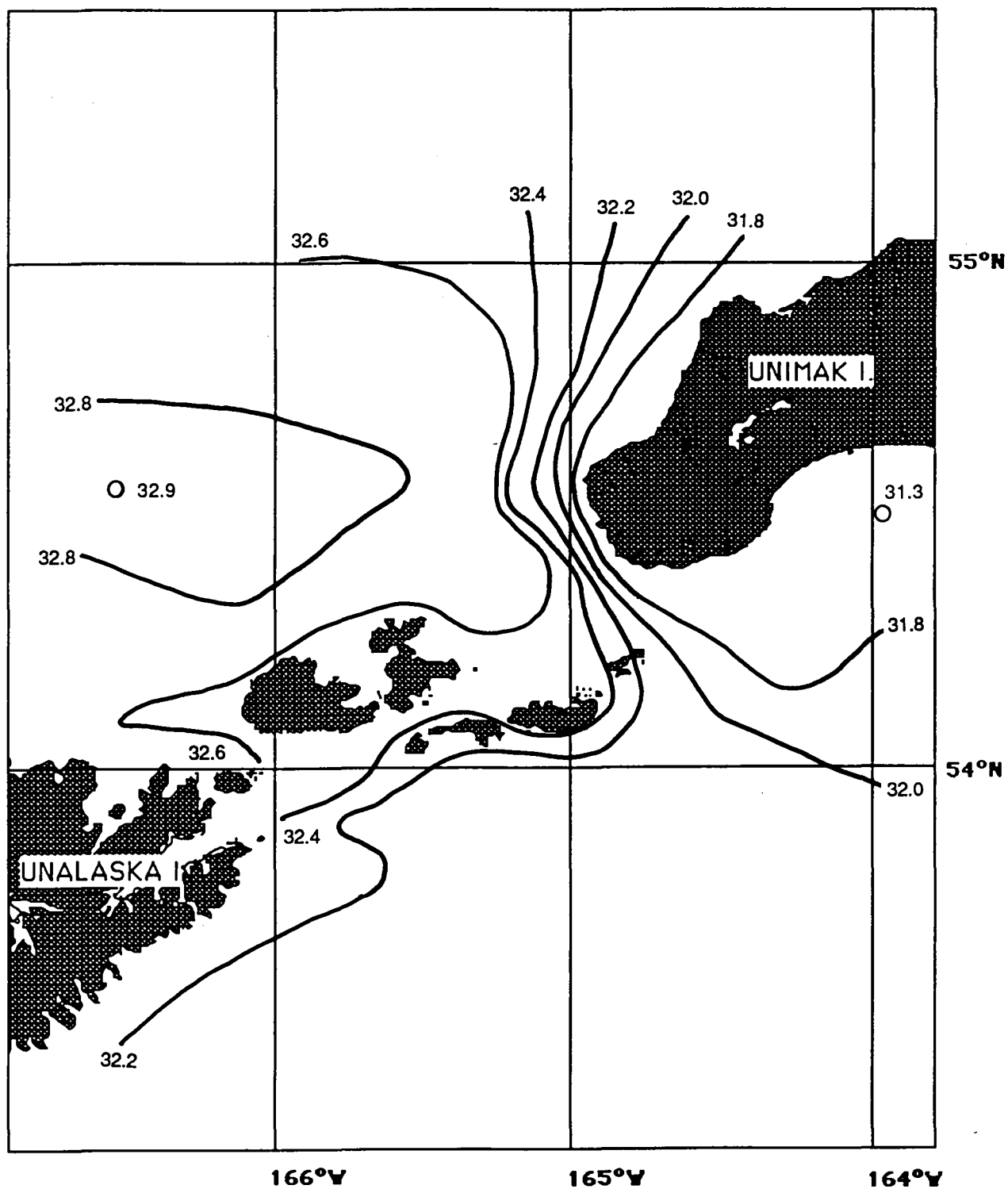


Figure 8. Sea surface salinities (ppt) in the Unimak Pass area, Alaska, during the fall cruise, 18 Sept-7 Oct, 1986.

## Winter 1987 : CTD Transects

Winter sea-surface temperatures at stations in the Unimak Pass area ranged from 3.0 to 4.5° C. Warmest waters occurred in the southernmost portions of the study area at the edge of the Gulf of Alaska continental shelf (Fig. 9). Coolest waters were found to the south and north of Unimak Island.

Surface salinities during the winter (31.0-32.5 ppt) were again lowest around Unimak Island, but Alaska Coastal Water (<31.8 ppt) extended farther west than during the fall season (compare Figs. 8 and 10). In the southeast corner of the study area, salinities exceeded 32.4 ppt. The most saline water (>32.8 ppt) occurred in the Bering Sea north of Unalaska Island. Well-mixed waters occurred in Avatanak Strait (Stations 5.1, 6.1), Rootok Strait (Station 9.3), Ugamak Strait (Station 9.7), Akutan Pass (Station 21.3), the west side of Unalga Island (Station 14.4), the south side of Unimak Pass (Station 31.2), the south side of Ugamak Island, and the waters north of Unimak, Akun, and Akutan islands (Chapter 10; Appendix B-2, this volume). Depths at well-mixed stations ranged from 24-100 m. Vertical (surface-to-bottom) temperature and salinity gradients at 15 well-mixed stations varied by only 0.01-0.08° C and 0.01-0.2 ppt, respectively, over the entire water column.

At many stations, surface temperatures were 0.5-1.0° C colder than they were 100-200 m deeper, a reportedly common feature in the study area during winter (Dodimead et al. 1963). Winter advection and cooling of surface waters created situations where "reverse" thermoclines (increasing temperature with depth), were most pronounced at deeper stations. Most stations during the winter cruise did not reveal strong pycnoclines within the foraging depths of seabirds, although some casts did indicate gradual pycnoclines at depths exceeding 100 m (Chapter 10; Appendix B-2, this volume)

## Spring 1987: CTD Transects

The range of sea surface temperature during spring (3.3-6.0° C) was greater than during winter but less than in the fall. As in the fall, warmest waters were at the edge of the continental shelf in the southeastern portion of the study area (Fig. 11). Coolest waters were situated north of Unimak Island. Most of the remaining portion of the study area had surface temperatures of 4.0-4.5° C.

During spring, the 31.8 ppt isoline (limit of Alaska Coastal Water) stretched from the southeastern part of the study area past Tigalda Island and then north to more than 50 km offshore from Unimak Island (Fig. 12). At no other season was the apparent westward extent of Alaska Coastal Water greater. The most saline water (32.4-32.8 ppt) was located north of Unalaska Island over the Bering Sea continental slope, as during the fall and winter cruises.

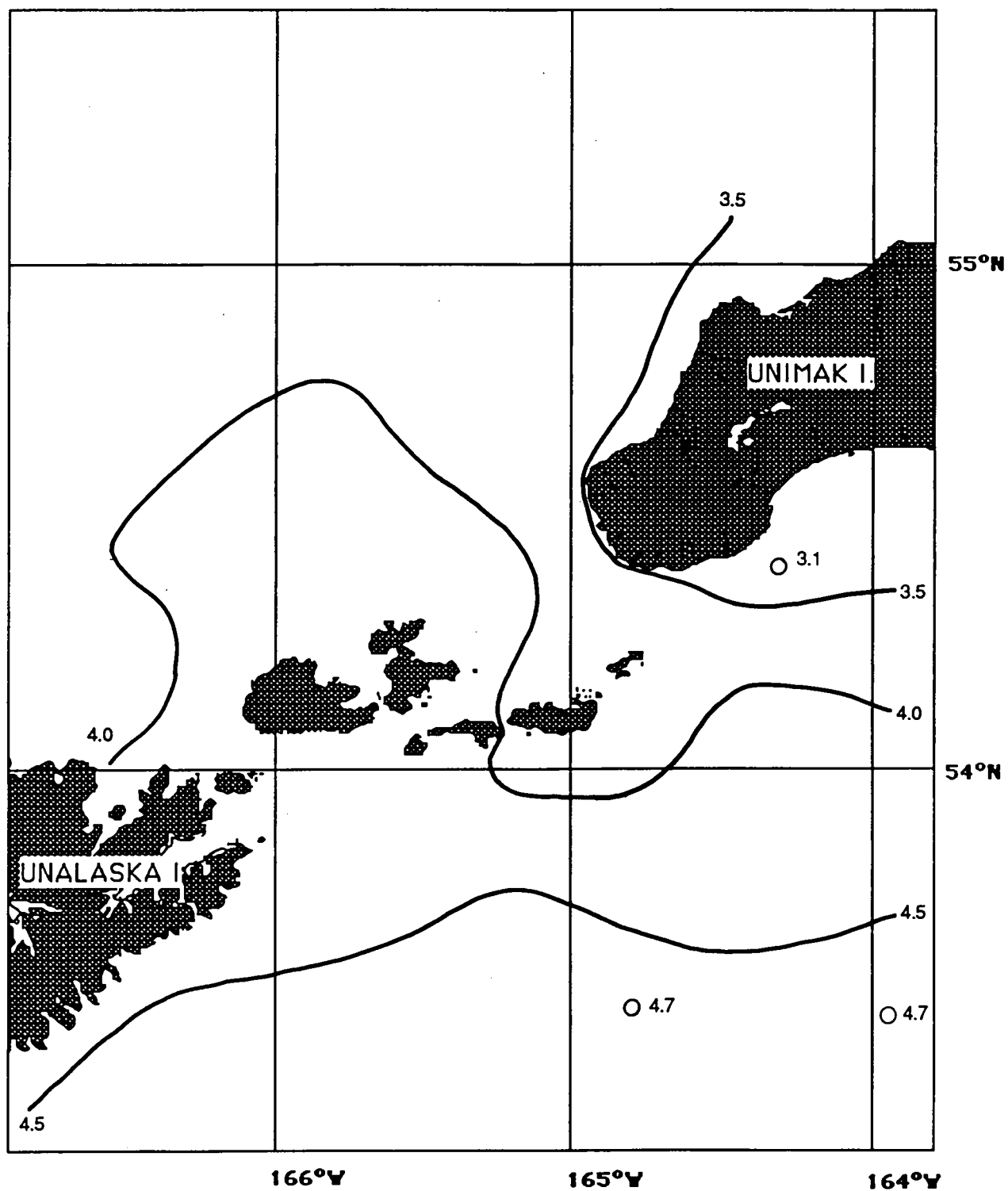


Figure 9. Sea surface temperatures (degrees C) in the Unimak Pass area, Alaska during the winter cruise, 14 Feb-9 March, 1987.

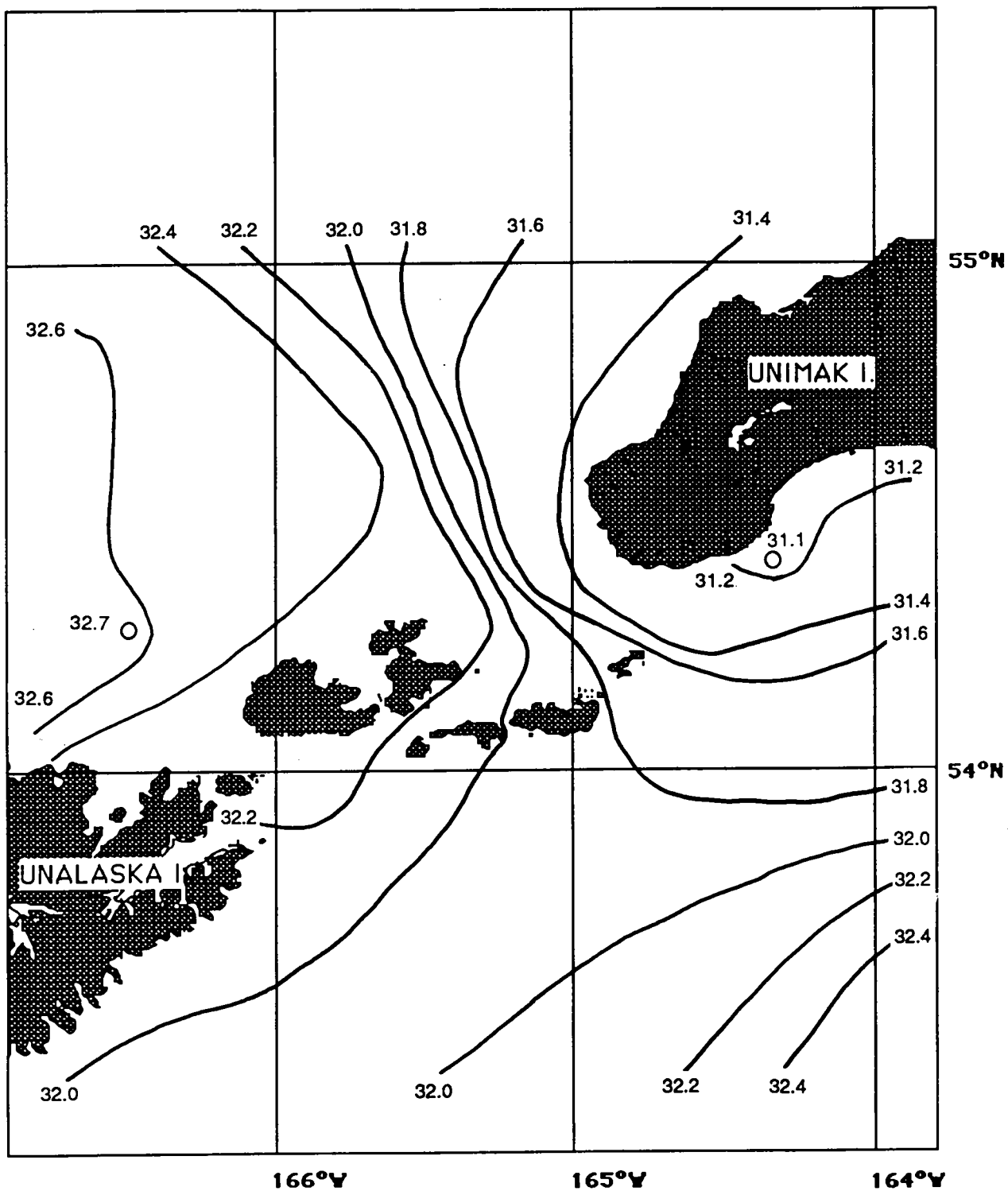


Figure 10. Sea surface salinities (ppt) in the Unimak Pass area, Alaska, during the winter cruise, 14 Feb-9 March, 1987.

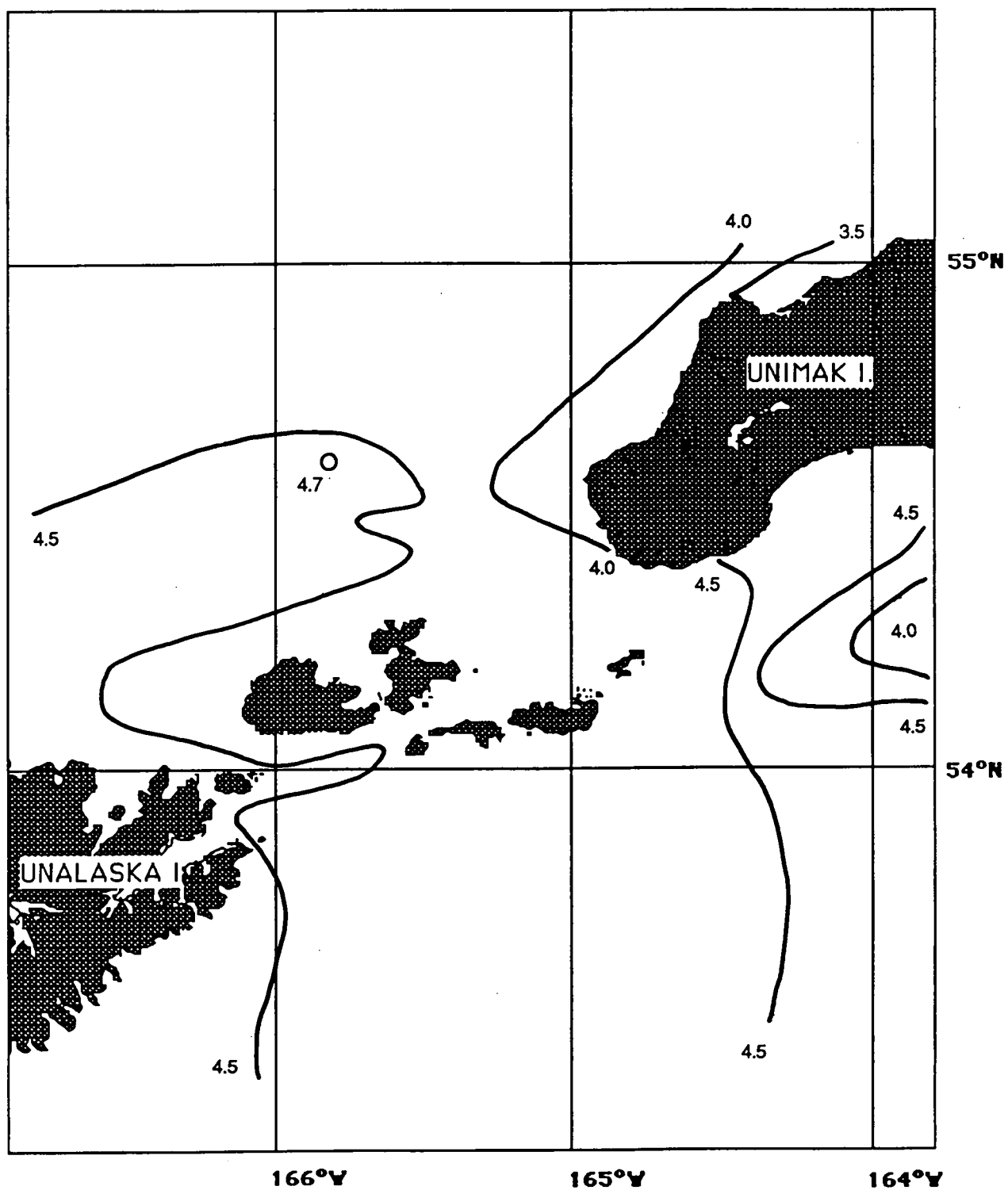


Figure 11. Sea surface temperatures (degrees C) in the Unimak Pass area, Alaska during the spring cruise, 21 April-14 May, 1987.

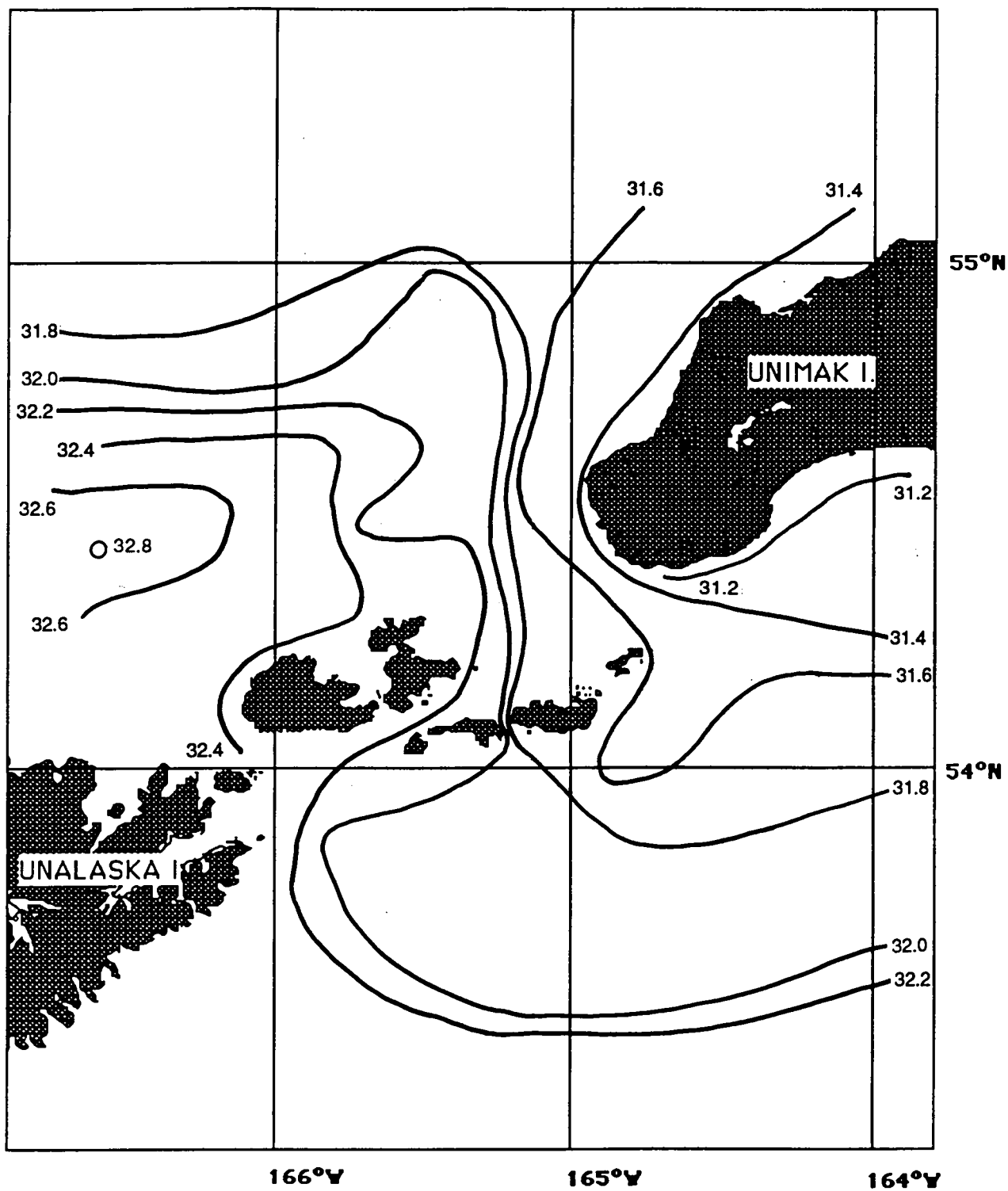


Figure 12. Sea surface salinities (ppt) in the Unimak Pass area, Alaska, during the spring cruise, 21 April-14 May, 1987.

Well-mixed waters occurred in Avatanak Strait (Stations 5.1, 6.1), Akutan Pass (Station 21.3), east of Unalga Pass (Station 22.1), on the east side of Unimak Pass (Station 31.2), the northwest side of Tigalda Island (Station 9.2), north and south of Ugamak Island (Stations 9.8 and 22.4, respectively), south of the Baby Islands near Baby Pass (Station 14.4), north of Unimak Island (Stations 17.1, 17.2, 17.3), and southeast of Sedanka Island (Station 29.2) (Chapter 10; Appendix B-3, this volume). Water depths at these well-mixed stations varied from 28-100 m. Vertical property gradients varied from 0.001-0.07° C and 0.01-0.20 ppt over the entire water column.

Few stations had strong pycnoclines in the water column during spring (see Chapter 10: Appendix A, B-3; this volume). As in winter, some stations showed "reverse" thermoclines with surface temperatures 1.0-1.5° C colder than those at depth (e.g., Station 15.1). Most shallow stations typically showed vertical temperature and salinity gradients of only a few tenths of a degree centigrade or tenths of a ppt, respectively.

### **Winter 1987 : Infrared Imagery**

Seven infrared images from the 4Z enhancement curve were obtained for the Unimak Pass study area between 28 February and 6 March 1987. Four additional images from the 94Z curve were obtained between 2 and 5 March 1987. Satellite-detected isotherms were oriented primarily southeast to northwest, normal to the Alaska Peninsula and eastern Aleutian arc. As shown by the CTD data from shipboard stations, the warmest surface waters were in the southern part of the study area near the edge of the Gulf of Alaska continental shelf. Coldest waters were to the north and east of Unimak Island. This band of cold water expanded and contracted in an onshore-offshore direction by about 8-12 km during the 8-day period. For the most part, surface waters were isothermal in the immediate study area, and no strong horizontal gradients were detected by the imagery.

### **All Cruise Periods : Sea Surface Thermal Charts**

Sea Surface Thermal Analyses charts (based on remote-sensing data) showed the same general patterns in surface temperature distributions as did the CTD shipboard measurements. Surface temperatures varied from 8 to 11° C during the fall cruise period. Although the scale of isotherm presentation was too coarse to provide much detail for the Unimak Pass study area, colder water (<8° C) was present northwest of Unimak Pass during 17-18 and 26-28 September. Charts for the winter period showed surface temperatures of 3-4° C, except for 29 February to 3 March when a water mass 5-6° C was present north and west of Akun, Akutan, and Unalaska Islands. During the spring

cruise period, surface temperatures varied from 3-6° C and no patterns were evident from the charts.

### CTD Casts for Tidal Effects

Time series CTD casts at four stations provided insight into the effects of tides on property distributions in the water column. Casts were made during all seasons sampled.

On 7 October 1986 seven casts were conducted at Station 26.2 east of Unalga Island (Table 1). Patterns in vertical property gradients varied little during the seven cast periods. At 0520 ADT (Station 26.2a), waters were slightly more stratified than during the other casts, but temperatures still varied only by 0.08° C and salinity by 0.06 ppt from top to bottom. The most mixed periods occurred at 1312 hrs (Station 26.2e) and 1708 hrs ADT (Station 26.2g). Property gradients were least apparent during these periods. The CTD casts indicate that mixing persisted throughout the 12-hr sampling period.

On 1 March 1987 Station 21.3 was sampled once, and on 6-7 March it was sampled six times (Table 2). All casts showed that vertical property gradients varied little among cast periods. Top-to-bottom temperatures and salinities varied by no more than 0.03° C and 0.05 ppt, respectively.

On 7 and 8 May 1987, six casts were made at Station 6.4 north of Akun Island on the east side of Unimak Pass (Table 3). This time-series showed the greatest variation among cast periods. The first three casts (from 2300 to 0100 hrs) showed a relatively pronounced pycnocline starting at about 25 m and extending to 60 m. The pycnocline was less abrupt during the next three casts (0300 and 0700 hrs on 8 May). Surface values of sigma-t varied from 25.6 to 25.8. The three earliest casts noted above had the lowest sigma-t values. Thus, from 2100 hrs on 7 May to 0100 hrs on 8 May, less dense water occurred at the station. The three late casts had a small (0.02° C) "reverse" thermocline extending from 10 to 20 m.

On 11 and 12 May 1987 Station 21.1 north of Unalaska Island was sampled five times (Table 4). Even though this station was deep (ca. 500 m), vertical temperature gradients ranged only from 3.6 to 4.7° C. Three of the five casts (Stations 21.1a and b on 11 May, Station 21.1 on 12 May) showed a 0.15° C "reverse" thermocline at 25 m. All five casts showed "reverse" thermoclines at 150 m, and from 250 to 300 m. Sigma-t patterns were similar for all five casts, indicating little change in vertical property gradients with respect to tidal period at this station.

## Nutrient Distributions and Upwelling

Nitrate concentrations in the water column varied both spatially and temporally, as shown by water samples taken at sampling stations in spring, fall, and winter (Figs. 13-15). Nitrates tend to be rapidly consumed by phytoplankton in surface waters and are generally found in low concentrations. High levels of nitrates in surface waters are indicative of upwelling. The patterns of nitrate variation observed suggest that upwelling occurred on the Bering Sea side of the Aleutians; the gradient in surface nitrate concentrations along the Aleutians indicated that most upwelling was located to the west of our study area.

Surface nitrate concentrations in the along-shelf transect during March 1987 (Fig. 6) were greatest ( $>20 \mu\text{M}$ ) north of Unalaska and Akutan islands over the continental slope of the Bering Sea (Fig. 13). In Unimak Pass, surface nitrate concentrations were higher during winter and at the northern stations (Figs. 14 and 15). Transects of temperature and salinity show that this area was well-mixed during each season of the study (see Chapter 10: Appendix A).

## DISCUSSION

Several results from this study confirm the findings of previous investigations relative to the distributions of physicochemical qualities of water and the sources of water masses. Distributions of salinity, temperature, and nutrient levels allow refinement of some of the previous notions about water sources, water quality distributions, and the effects of these on the biota.

Low-salinity ( $<31.8$  ppt) Alaska Coastal Current Water (ACW) was confined to the east side of Unimak Pass near Unimak Island. This pattern persisted for all three seasons when cruises were conducted, though ACW extended farthest west in spring. A region of relatively rapid surface temperature change from east to west indicated the presence of a front, somewhere about the middle of Unimak Pass proper, that separated ACW from the adjacent water mass to the west. The nitrate concentrations measured in this study also indicated the presence of a front in the same area west of Unimak Island. No water with the characteristics of ACW occurred west of Unimak Pass on the Gulf of Alaska side of the Aleutians.

Water temperatures changed more among seasons in and near shallow areas, as would be expected due to the greater mass and consequent temperature stability of the waters off the shelf vs. water on the shelf. Water in winter and spring was warmest nearest the shelf breaks, particularly the Gulf of Alaska shelfbreak to the south. Conversely, in fall, temperatures closest to shore were warmer than those near deeper waters, again as expected because of the shallower on-shelf water being warmed the preceding summer.

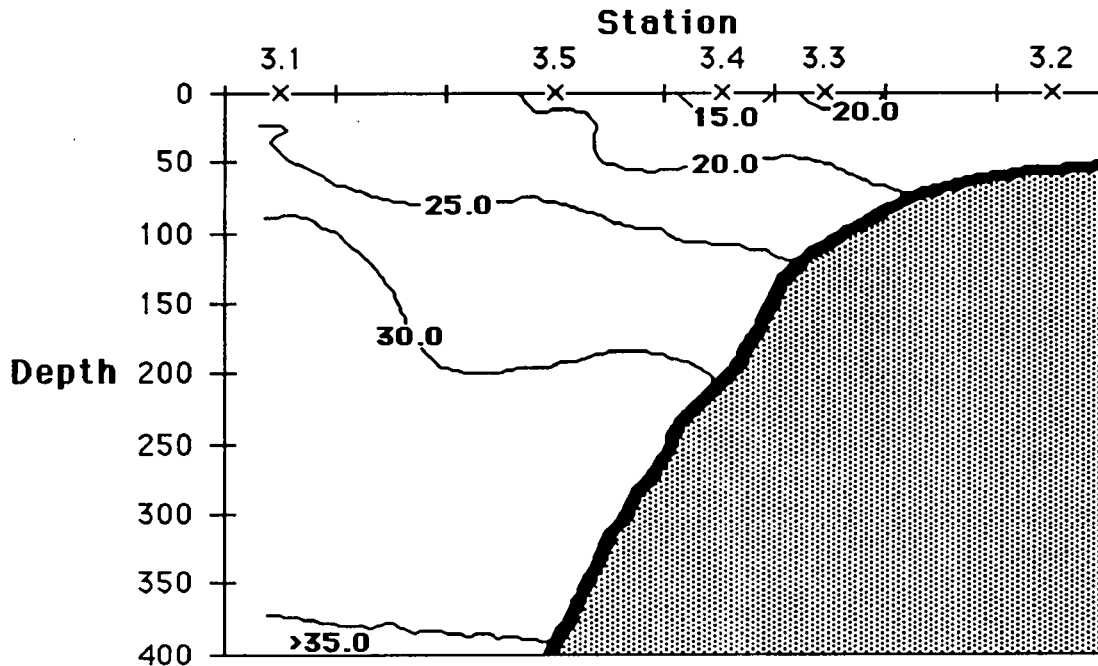


Fig. 13. Isolines of nitrate (in  $\mu\text{M}$ ) on the north Aleutian Shelf during March 1987, Unimak Pass area, Alaska (see Fig. 5 for station locations).

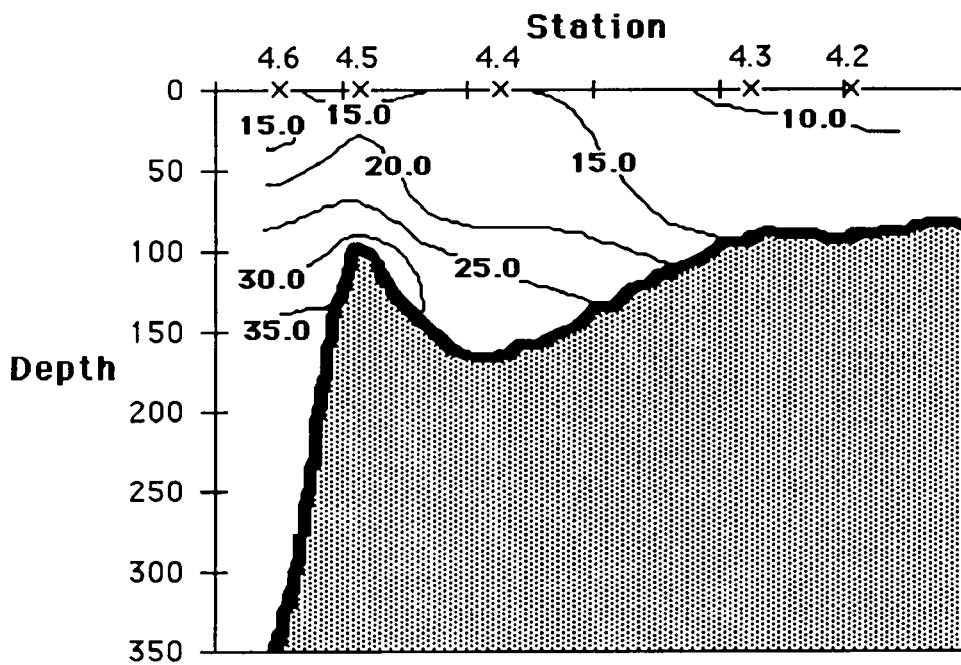


Fig. 14. Isolines of nitrate (in  $\mu\text{M}$ ) through Unimak Pass during September 1986 (see Fig. 6 for station locations).

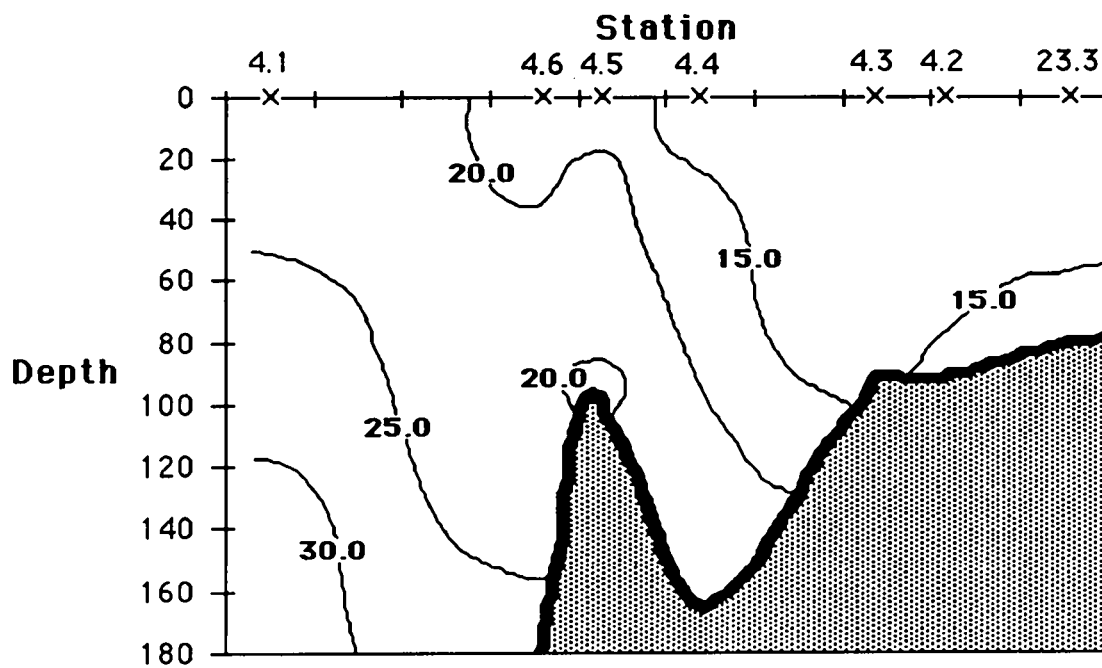


Fig. 15. Isolines of nitrate (in  $\mu\text{M}$ ) through Unimak Pass during February 1987 (see Fig. 6 for station locations).

Vertical casts revealed that, in winter and spring, cold water formed near the surface as a result of winter cooling and convection. A zone of warmer water lay under this layer and over colder water, resulting in patterns of "reverse" thermoclines; these thermoclines occurred at depths beyond the normal foraging depths of most seabirds.

Nitrate surface concentrations greater than 15  $\mu\text{M}$  in the middle of both Unimak and Akutan passes provided evidence that mixing was supplying nutrient-rich water to the euphotic zone in these areas. The enrichment appeared to come from the northwest, as indicated by increases in surface concentrations in that direction.

Nutrient concentrations were highest west of Unimak Pass during both the fall and winter cruises. Within the pass, isolines of nutrient concentration sloped downward to the southeast. This argues against upwelling occurring as the result of deep Gulf of Alaska water being vertically transported over the shallow sill of Unimak Pass. Rather, as suggested above, the nutrient enrichment probably comes from the west as a result of upwelling on the north side of the Aleutian Chain.

Four different water masses appeared to be present during each of the three cruises. These water masses are characterized below with respect to their mixing regimes and surface salinities, conservative properties which vary little seasonally in contrast to surface temperature. Typical distributions of water masses in the study area are illustrated in Figure 16.

Alaska Coastal Current Water (ACW) was identified by surface salinities  $<31.8$  ppt and occurred only on the east side of Unimak Pass. It appeared to represent the Alaska Coastal Current swinging in a U-turn around the end of Unimak Island, as had been reported by earlier workers.

Shelf Break Water (SBW) seemed to occur on the north side of the Aleutians over or near the Bering Sea shelf break, as reported by Kinder and Schumacher (1981). Water in this area was characterized by surface salinities  $>32.6$  ppt and occurred only in the northwestern portion of the study area north of Unalaska and Akutan islands.

What in this report is called Gulf of Alaska Water (GAW; surface salinities between 31.8 and 32.6 ppt) was prevalent on the Gulf of Alaska side of the island arc and extended through the western part of Unimak Pass to the north-central portion of the study area. GAW occupied the greatest areal extent of the four water mass types.

Tidally-mixed Water (TMW) was characterized by little or no variation in property gradients between surface and bottom waters. TMW occurred in

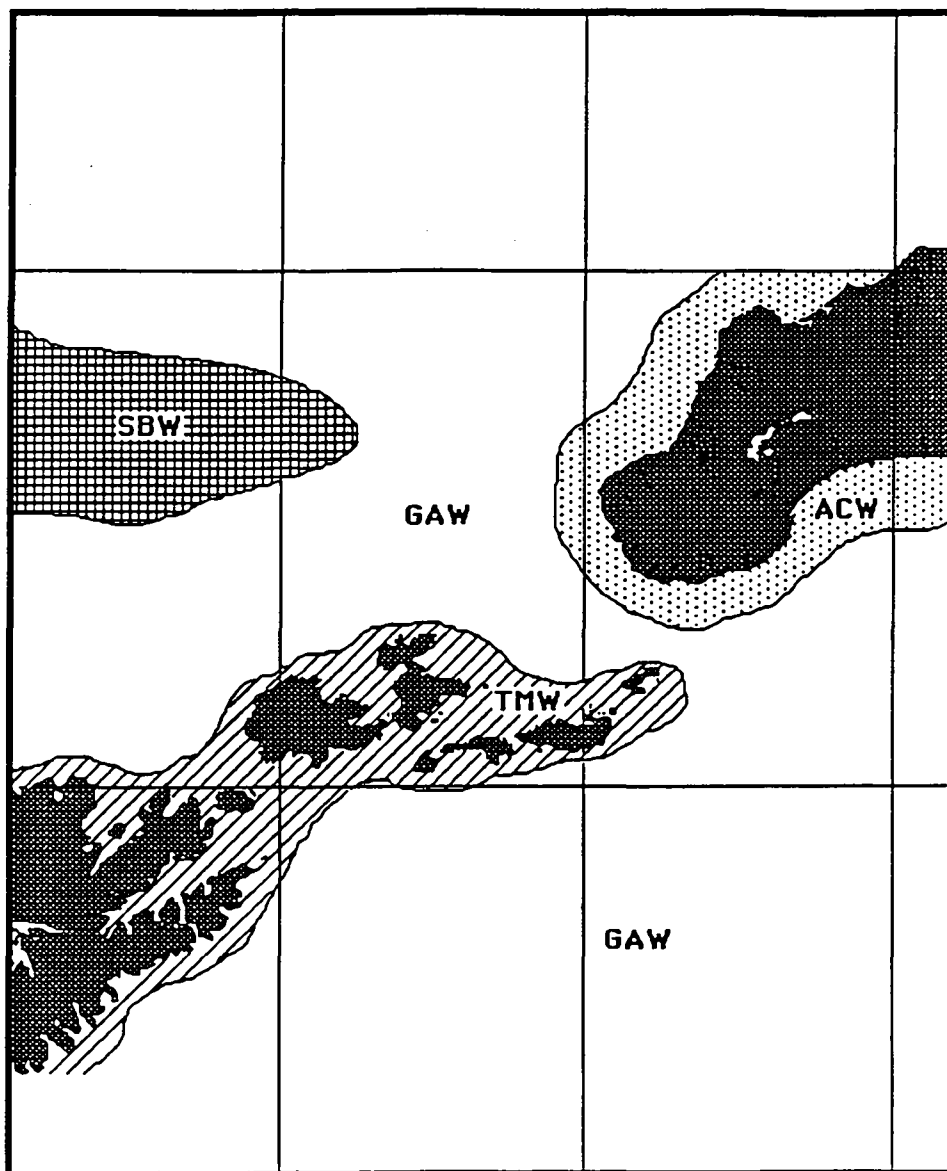


Figure 16. Schematic map of the principal water masses in the Unimak Pass area, Alaska (ACW=Alaska Coastal Water; GAW=Gulf of Alaska Water; SBW=Shelf Break Water; TMW=Tidally-mixed Water). Actual boundaries varied between cruises.

relatively shallow (<100 m) waters, generally within 25 km of land, and was the dominant water mass in Akutan and Unalga passes; Ugamak, Derbin, Avatanak, Rootok, and Akun straits; and around all islands except Unimak Island. TMW appeared to be most similar to GAW with respect to its salinity and temperature regime.

Typical Alaska Stream Water, with temperatures of 4-5° C and salinities of 32.9 ppt down to 100 m (Takenouti and Ohtani 1974), was not encountered in this study.

### RECOMMENDED FURTHER RESEARCH

The combined results of this study and the North Aleutian Shelf Ecological Process Study (Truett 1987) document a gradient in nutrient availability, and a generally parallel trend in biological activity, oriented from west to east along the north side of the eastern Aleutians and the Alaska Peninsula. The source of the nutrients which promote the rich concentrations of birds and other marine life in these areas is evidently to the west of the Unimak Pass study area. Further sampling to the west would be useful to identify the origins of these nutrients, which are suspected to be near Samalga Pass.

Additional sampling for nutrients would be useful, especially during the fall when the major concentrations of marine birds occur in the northwest part of Unimak Pass. Unfortunately, we did not do a west-east nutrient transect during fall. Otherwise, the oceanographic needs for the purposes of the marine bird and mammal studies are largely filled, though there is probably still much of interest in this area for oceanographers who have broader objectives.

### ACKNOWLEDGEMENTS

We are indebted to the the entire crew of the Miller Freeman for their cooperation and assistance in making this cruise such a success. The concern and interest expressed by all personnel from the galley through the engineering department and the deck crew was beyond our expectations.

Of particular note are the efforts of the ship's survey technician, Dan Dougherty, who operated the CTD and performed all the calibrations and made all the ancillary collections. Dan also routinely checked for any oceanographic features, such as pycnoclines, that would influence the depths we wished to sample for nutrients. We are deeply indebted for his help.

Chirk Chu of the Institute of Marine Science, University of Alaska, Fairbanks, reduced the voluminous CTD data tapes into more useful and accessible forms for our analysis. We appreciate his quick work.

Jo Young prepared the base map for use in the graphics. Terry Carpenter, Robert Dillinger, Benny Gallaway, and Joe Truett provided useful edits of various drafts.

#### LITERATURE CITED

- Craig, P. C. 1987. Fish resources. Pp. 219-353. In: J.C.Truett (ed.). Environmental characterization and biological utilization of the North Aleutian Shelf nearshore zone. U. S. Dep. Commer., NOAA, OCSEAP Final Rep. 60:1-563.
- Dodimead, A. J., F. Favorite and T. Hirano. 1963. Review of oceanography of the subarctic Pacific region. Int. North Pacific Fish. Comm. Bull. 13. 195 p.
- Dugdale, R. C. and J. J. Goering. 1967. Uptake of new and regenerated forms of nitrogen in primary production. Limnol. Oceanogr. 12:196-206.
- Favorite, F. 1974. Flow into the Bering Sea through the Aleutian Island passes. Pp. 3-37. In: D. W. Hood and E. J. Kelley (eds.). Oceanography of the Bering Sea. Univ. Alaska Inst. Marine Sci. Occ. Pub. No. 2, Fairbanks, AK.
- Hood, D. W. 1986. Physical and chemical processes. Pp. 183-222. In: J. C. Truett and P. C. Craig (eds.). Evaluation of environmental information for the Unimak Pass area, Alaska. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 58:1-392.
- Hood, D. W. and J. J. Kelley. 1976. Evaluation of mean vertical transports in an upwelling system by CO<sub>2</sub> measurements. Mar. Sci. Comm. 2(6):386-411.
- Hughes, F. W., L. K. Coachman and K. Aagaard. 1974. Circulation, transport and water exchange in the western Bering Sea. Pp. 40-59. In: D. W. Hood and E. J. Kelley (eds.). Oceanography of the Bering Sea. Univ. Alaska Inst. Marine Sci. Occas. Pub. No. 2. Fairbanks.
- Kelley, J. J. and D. W. Hood. 1974. Upwelling in the Bering Sea near the Aleutian Islands. Tethys 6(1-2):149-156.
- Kelley, J. J., L. L. Longerich and D. W. Hood. 1971. Effect of upwelling, mixing and high primary production on CO<sub>2</sub> concentrations in surface waters of the Bering Sea. J. Geophys. Res. 76:8687-8693.

- Kinder, T. H., and J. D. Schumacher. 1981. Circulation over the continental shelf of the southeastern Bering Sea. Pp. 53-75. In: D. W. Hood and J. A. Calder (eds.). The Eastern Bering Sea shelf: oceanography and resources. Vol. 1. U.S. Dep. Commer., NOAA, OMPA, Univ. Washington Press, Seattle.
- Koike, I., K. Furuya and A. Hattori. 1979. Continuous measurements of nitrogenous compounds and chlorophyll-a in surface waters of the Bering Sea. Pp. 221-222. In: Proc. 1979 Spring meeting of Oceanogr. Soc. Japan.
- Koike, I., K. Furuya, H. Otake, T. Nakai, T. Nemoto and A. Hattori. 1982. Horizontal distributions of surface chlorophyll-a and nitrogenous nutrients near Bering Strait and Unimak Pass. DeepSea Res. 29:149-152.
- Nof, D. and S. H. Im. 1985. Suction through broad oceanic gaps. J. Phys. Oceanogr. 15:1721-1732.
- Schumacher, J. D., C. A. Pearson and J. E. Overland. 1982. On the exchange of water between the Gulf of Alaska and the Bering Sea through Unimak Pass. J. Geophys. Res. 87:5785-5795.
- Schumacher, J. D. and R. K. Reed. 1980. Coastal flow in the northwest Gulf of Alaska: The Kenai Current. J. Geophys. Res. 85:6680-6688.
- Strickland, J. D. H. and T. R. Parsons. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can. No. 167. 311 pp.
- Takenouti, A. Y. and K. Ohtani. 1974. Currents and water masses in the Bering Sea: A review of Japanese work. Pp. 39-57. In: D. W. Hood and E. J. Kelley (eds.). Oceanography of the Bering Sea. Univ. Alaska Inst. Mar. Sci. Occas. Pub. No. 2. Fairbanks, AK.
- Truett, J. C. (ed.) 1987. Environmental characterization and biological utilization of the North Aleutian Shelf nearshore zone. U. S. Dep. Commer., NOAA, OCSEAP Final Rep. 60:1-563.

## APPENDICES

Appendix A. Station number, date, time, depth, and location for stations on fall cruise MF-86-10.

Station (ADT)	Date (m)	Date (°N)	Time (°W)	Depth	Latitude	Longitude
2.1	19-Sep-1986	04:23	7	53.9390	165.7787	
2.2	19-Sep-1986	08:43	219	54.1608	166.3563	
2.3	19-Sep-1986	10:33	415	54.1575	166.3745	
2.4	19-Sep-1986	11:35	622	54.1705	166.3787	
2.5	19-Sep-1986	12:26	830	54.1825	166.3982	
3.2	20-Sep-1986	04:20	57	55.0050	164.5198	
3.3	20-Sep-1986	07:09	101	54.8327	165.1063	
3.4	20-Sep-1986	08:26	201	54.7508	165.3997	
3.5	20-Sep-1986	11:21	388	54.6173	165.8000	
4.1	20-Sep-1986	14:29	176	54.8647	166.5050	
4.3	21-Sep-1986	10:19	97	54.2295	164.6255	
4.2	21-Sep-1986	11:39	92	54.1663	164.3868	
4.4	21-Sep-1986	14:35	166	54.4203	165.1723	
4.5	21-Sep-1986	16:06	99	54.5315	165.4890	
4.6	21-Sep-1986	17:38	346	54.6213	165.6390	
9.1	22-Sep-1986	04:36	69	54.1730	164.8870	
9.2	22-Sep-1986	06:48	53	54.1218	165.2320	
9.3	22-Sep-1986	08:43	63	54.0850	165.5000	
6.1	22-Sep-1986	10:46	66	54.1520	165.3342	
6.2	22-Sep-1986	12:01	161	54.3063	165.4420	
6.3	22-Sep-1986	13:06	97	54.4243	165.5195	
14.1	23-Sep-1986	08:13	93	53.8002	165.4863	
14.2	23-Sep-1986	09:50	187	53.7147	165.2832	
15.1	23-Sep-1986	15:01	344	53.7453	164.0072	
13.1	24-Sep-1986	04:09	128	53.7780	165.8968	
14.4	24-Sep-1986	06:07	60	53.9712	166.0485	
13.2	24-Sep-1986	07:50	75	53.9047	166.1450	
14.3	24-Sep-1986	11:27	104	53.8257	165.5332	
8.1	24-Sep-1986	13:57	73	54.0432	165.4353	
5.1	24-Sep-1986	15:39	96	54.1052	165.4962	
16.1	25-Sep-1986	05:33	62	54.3345	164.7177	
16.2	25-Sep-1986	06:26	47	54.3792	164.7292	
17.4	25-Sep-1986	09:20	86	54.5583	165.1930	
17.3	25-Sep-1986	10:54	61	54.6340	164.9833	
17.2	25-Sep-1986	13:43	57	54.8158	164.6995	
17.1	25-Sep-1986	15:20	40	54.9680	164.4335	
17.8	26-Sep-1986	05:54	413	54.1087	166.4932	
16.3	26-Sep-1986	09:00	1560	54.2875	166.4747	
16.4	26-Sep-1986	12:56	841	54.3320	166.1438	
16.5	26-Sep-1986	15:25	439	54.5667	166.4970	
17.6	27-Sep-1986	05:01	57	54.2342	165.9943	
19.1	27-Sep-1986	07:23	168	54.4775	165.6262	
19.2	27-Sep-1986	10:12	129	54.5397	165.5520	
17.5	27-Sep-1986	12:33	66	54.3095	165.6585	
21.1	28-Sep-1986	10:14	1220	54.2942	166.4613	

Appendix A (cont.)

21.2	28-Sep-1986	12:18	102	54.1443	166.2728
21.3	28-Sep-1986	15:13	39	54.0233	166.0553
21.4	28-Sep-1986	16:34	86	53.8647	165.8042
21.5	28-Sep-1986	18:32	141	53.6662	165.5175
23.1	29-Sep-1986	03:59	86	54.4168	164.3077
23.2	29-Sep-1986	05:48	75	54.2378	163.9998
23.3	29-Sep-1986	08:06	78	54.0587	164.0010
23.4	29-Sep-1986	10:05	119	53.7825	163.9995
23.6	29-Sep-1986	15:15	1000	53.5112	164.0357
23.5	29-Sep-1986	17:09	1100	53.5952	164.0333
22.1	30-Sep-1986	07:18	108	53.9035	165.9372
22.2	30-Sep-1986	09:28	78	53.9045	165.7863
22.3	30-Sep-1986	10:41	94	53.9532	165.5953
25.1	30-Sep-1986	12:44	59	54.1018	165.6362
9.4	30-Sep-1986	13:43	75	54.0870	165.5010
9.6	01-Oct-1986	06:53	35	54.1333	165.0633
9.7	01-Oct-1986	07:57	55	54.2020	164.9215
9.8	01-Oct-1986	09:50	49	54.2245	164.8472
22.4	01-Oct-1986	11:45	40	54.2012	164.8020
22.5	01-Oct-1986	14:04	61	54.0547	165.0448
22.1	02-Oct-1986	05:10	66	54.0952	165.5572
22.8	02-Oct-1986	06:32	90	53.9995	165.2925
22.9	02-Oct-1986	08:53	89	53.9988	165.6713
29.2	02-Oct-1986	12:04	98	53.6140	165.9292
29.1	02-Oct-1986	14:18	101	53.4992	166.4355
30.1	03-Oct-1986	05:20	86	54.4870	164.0080
31.1	03-Oct-1986	08:49	66	54.3632	164.6578
31.2	03-Oct-1986	09:55	48	54.3750	164.8242
31.3	03-Oct-1986	13:06	95	54.0800	164.5533
31.4	03-Oct-1986	14:26	109	53.9652	164.4492
31.6	04-Oct-1986	05:09	126	54.9988	165.4930
31.5	04-Oct-1986	08:10	146	54.7758	165.2497
32.3	04-Oct-1986	09:59	173	54.6032	165.5152
32.2	04-Oct-1986	12:24	200	54.7840	165.7292
32.1	04-Oct-1986	14:28	138	54.9997	165.9985
32.6	05-Oct-1986	06:05	2000	53.4930	164.8245
32.5	05-Oct-1986	09:00	313	53.6718	164.7742
32.4	05-Oct-1986	10:22	103	53.8358	164.8005
32.3	05-Oct-1986	12:31	93	54.0022	164.8323
31.7	05-Oct-1986	14:18	86	54.1495	164.4893
26.2	07-Oct-1986	05:20	305	53.9023	166.1058
26.2	07-Oct-1986	07:11	310	53.9027	166.1150
26.2	07-Oct-1986	09:13	312	53.9018	166.1035
26.2	07-Oct-1986	11:13	320	53.9017	166.1277
26.2	07-Oct-1986	13:12	329	53.9012	166.1255
26.2	07-Oct-1986	15:03	330	53.9070	166.1295
26.2	07-Oct-1986	17:08	241	53.8940	166.1058

Appendix B. Station number, date, time, depth, and location for stations on winter cruise MF-87-02.

Station (AST)	Date (m)	Time (°N)	Depth (°W)	Latitude	Longitude
31.2	17-Feb-1987	03:06	64	54.3772	164.8510
31.5	17-Feb-1987	06:25	144	54.7810	165.2460
31.6	17-Feb-1987	08:03	126	54.9938	165.4817
23.6	17-Feb-1987	18:38	1912	53.4908	164.0045
23.5	18-Feb-1987	00:12	1738	53.5920	164.0625
31.4	18-Feb-1987	03:50	115	53.9782	164.4598
31.3	18-Feb-1987	06:26	77	54.2392	164.7137
4.1	18-Feb-1987	18:22	176	54.8642	166.5202
4.6	18-Feb-1987	22:46	342	54.6208	165.6382
4.5	19-Feb-1987	00:31	99	54.5315	165.4883
4.4	19-Feb-1987	02:19	161	54.4235	165.1695
4.3	19-Feb-1987	04:52	86	54.2238	164.6215
4.2	19-Feb-1987	06:10	93	54.1613	164.3888
23.3	19-Feb-1987	07:59	82	54.0587	164.0005
29.1	19-Feb-1987	16:51	104	53.4978	166.4337
29.2	19-Feb-1987	21:35	97	53.6167	165.9252
21.5	19-Feb-1987	23:21	148	53.6617	165.5150
17.1	22-Feb-1987	18:58	40	54.9807	164.3962
17.3	23-Feb-1987	18:37	60	54.6282	164.9952
17.2	23-Feb-1987	21:53	60	54.8223	164.6973
3.3	24-Feb-1987	02:54	103	54.8330	165.1052
3.2	24-Feb-1987	06:04	57	55.0117	164.5167
3.1	24-Feb-1987	18:59	574	54.4255	166.5210
3.5	24-Feb-1987	22:54	393	54.6200	165.8052
3.4	25-Feb-1987	01:15	206	54.7472	165.4032
17.4	25-Feb-1987	04:14	88	54.5605	165.1995
22.9	25-Feb-1987	19:14	91	54.0225	165.6765
13.2	25-Feb-1987	21:40	137	53.9050	166.1343
14.4	25-Feb-1987	23:11	59	53.9743	166.0410
9.3	26-Feb-1987	01:42	88	54.0952	165.4933
9.2	26-Feb-1987	04:08	60	54.1300	165.2347
6.1	26-Feb-1987	05:40	66	54.1558	165.3267
10.3	26-Feb-1987	18:49	84	54.0662	166.3660
2.2	26-Feb-1987	20:35	291	54.1662	166.3578
46.1	26-Feb-1987	22:27	29	54.0152	166.1203
17.8	27-Feb-1987	02:27	706	54.1167	166.4742
17.6	27-Feb-1987	06:16	96	54.2433	165.9922
32.6	27-Feb-1987	19:38	1673	53.5038	164.8332
14.2	27-Feb-1987	23:32	192	53.7133	165.2810
14.3	28-Feb-1987	01:55	105	53.8270	165.5245
22.3	28-Feb-1987	03:54	99	53.9655	165.5953
22.1	28-Feb-1987	06:25	91	53.9223	165.9400
30.1	28-Feb-1987	18:54	108	54.4977	164.0290
23.2	28-Feb-1987	21:18	75	54.2262	164.0162
32.4	01-Mar-1987	01:16	107	53.8275	164.8065
22.5	01-Mar-1987	03:40	61	54.0525	165.0497
22.8	01-Mar-1987	05:56	73	54.0028	165.2898
21.3	01-Mar-1987	19:34	77	54.0190	166.0287

Appendix B (cont.)

21.1	01-Mar-1987	22:36	1085	54.2955	166.4517
21.2	02-Mar-1987	01:29	123	54.1533	166.2728
21.4	02-Mar-1987	04:48	88	53.8673	165.8010
21.5	02-Mar-1987	06:47	146	53.6667	165.5133
21.6	02-Mar-1987	08:32	1006	53.4960	165.2710
22.4	02-Mar-1987	18:55	51	54.2005	164.7885
32.5	02-Mar-1987	22:16	326	53.6692	164.7747
32.7	03-Mar-1987	01:41	87	54.0177	164.8472
22.8	03-Mar-1987	03:58	84	53.9935	165.3105
22.5	03-Mar-1987	05:42	68	54.0503	165.0600
5.1	03-Mar-1987	20:57	104	54.1103	165.4738
9.7	03-Mar-1987	23:41	53	54.2088	164.9195
31.1	04-Mar-1987	01:45	66	54.3622	164.6637
23.1	04-Mar-1987	03:43	110	54.3968	164.3765
17.5	04-Mar-1987	18:11	80	54.3163	165.6668
6.2	04-Mar-1987	19:53	143	54.3065	165.4547
6.3	04-Mar-1987	21:58	95	54.4217	165.5282
32.2	05-Mar-1987	00:35	196	54.7823	165.8215
32.3	05-Mar-1987	03:03	173	54.6062	165.5143
3.2	05-Mar-1987	18:44	58	55.0240	164.5270
3.3	05-Mar-1987	21:17	104	54.8335	165.1052
3.4	05-Mar-1987	23:01	210	54.7485	165.4092
3.5	06-Mar-1987	00:55	393	54.6188	165.8053
3.1	06-Mar-1987	04:44	569	54.4245	166.5275
21.3	06-Mar-1987	20:21	43	54.0237	166.0613
21.3	06-Mar-1987	22:01	48	54.0247	166.0448
21.3	07-Mar-1987	00:08	63	54.0258	166.0737
21.3	07-Mar-1987	02:07	53	54.0213	166.0647
21.3	07-Mar-1987	04:03	44	54.0218	166.0742
21.3	07-Mar-1987	06:04	71	54.0273	166.0877

Appendix C. Station number, date, time, depth, and location for stations on spring cruise MF-87-05.

Station (ADT)	Date (m)	Time (°N)	Depth (°W)	Latitude	Longitude
22.1	23-Apr-1987	21:38	105	53.9122	165.9405
22.3	23-Apr-1987	23:14	94	53.9740	165.6048
22.5	24-Apr-1987	02:16	61	54.0530	165.0227
23.2	24-Apr-1987	06:45	75	54.2220	164.0158
29.1	24-Apr-1987	19:48	103	53.4983	166.4378
29.2	24-Apr-1987	22:26	96	53.6173	165.9283
14.3	25-Apr-1987	01:14	106	53.8253	165.5268
14.2	25-Apr-1987	03:18	192	53.7107	165.2875
32.6	25-Apr-1987	06:26	2195	53.4890	164.8345
21.1	25-Apr-1987	19:12	1050	54.2920	166.4568
21.2	25-Apr-1987	21:59	106	54.1465	166.2703
21.3	25-Apr-1987	23:52	46	54.0200	166.0668
21.8	26-Apr-1987	02:39	88	53.8660	165.8110
21.5	26-Apr-1987	04:46	144	53.6592	165.5193
21.6	26-Apr-1987	07:04	1175	53.4932	165.2762
32.5	26-Apr-1987	1:21	392	53.6570	164.7712
32.4	26-Apr-1987	22:14	106	53.8293	164.8013
15.1	27-Apr-1987	03:35	450	53.7355	164.0198
23.5	27-Apr-1987	06:05	1700	53.5953	164.0768
32.1	27-Apr-1987	19:25	140	55.0035	165.9975
32.2	27-Apr-1987	21:50	190	54.7900	165.8262
32.3	28-Apr-1987	00:39	182	54.6092	165.5133
17.5	28-Apr-1987	04:06	86	54.3203	165.6957
17.6	28-Apr-1987	06:15	102	54.2538	165.9930
17.1	28-Apr-1987	19:03	42	54.9853	164.3930
17.2	28-Apr-1987	21:45	60	54.8260	164.6922
17.3	29-Apr-1987	00:18	66	54.6242	165.0047
17.4	29-Apr-1987	02:01	81	54.5727	165.1973
19.1	29-Apr-1987	04:29	182	54.4832	165.6307
22.9	29-Apr-1987	19:16	93	54.0148	165.6897
5.1	29-Apr-1987	21:22	106	54.1055	165.4695
6.1	29-Apr-1987	23:29	68	54.1573	165.3247
9.2	30-Apr-1987	01:19	58	54.1312	165.2337
22.7	30-Apr-1987	03:05	86	53.9960	165.2218
22.8	30-Apr-1987	05:09	87	53.9957	165.2953
32.7	30-Apr-1987	19:38	91	53.9990	164.8470
22.4	30-Apr-1987	22:03	46	54.2005	164.7948
9.8	30-Apr-1987	23:59	50	54.2243	164.8582
9.7	01-May-1987	01:53	56	54.2155	164.9158
22.5	01-May-1987	04:04	61	54.0522	165.0387
22.7	01-May-1987	05:49	79	54.0278	165.1687
6.2	01-May-1987	19:06	146	54.3105	165.4527
6.3	01-May-1987	21:24	98	54.4275	165.5257
16.4	02-May-1987	00:39	779	54.3417	166.1378
17.8	02-May-1987	05:26	640	54.1148	166.4757
22.1	02-May-1987	19:37	94	54.0942	165.5488
46.1	02-May-1987	21:53	31	54.0168	166.1257
14.4	02-May-1987	23:40	39	53.9843	166.0453

Appendix C (cont.)

13.2	03-May-1987	01:35	118	53.9108	166.1313
43.1	03-May-1987	03:38	235	53.8238	166.3423
3.2	04-May-1987	19:22	57	55.0132	164.5207
3.3	04-May-1987	22:49	107	54.8302	165.1157
3.4	05-May-1987	01:12	202	54.7563	165.4073
3.5	05-May-1987	04:12	392	54.6230	165.8263
3.1	05-May-1987	07:25	556	54.4347	166.5282
23.3	05-May-1987	19:10	80	54.0537	164.0065
4.2	05-May-1987	20:41	91	54.1630	164.3877
4.3	05-May-1987	21:51	91	54.2263	164.6242
4.4	05-May-1987	23:49	171	54.4233	165.1777
4.5	06-May-1987	01:13	98	54.5323	165.4917
4.6	06-May-1987	02:12	342	54.6183	165.6405
4.1	06-May-1987	07:01	175	54.8647	166.5238
10.1	06-May-1987	19:29	93	54.4218	165.5430
10.3	07-May-1987	06:41	83	54.0628	166.3547
6.4	07-May-1987	21:02	102	54.3900	165.4890
6.4	07-May-1987	22:57	98	54.3912	165.4920
6.4	08-May-1987	01:00	97	54.3897	165.4967
6.4	08-May-1987	03:00	97	54.3895	165.4962
6.4	08-May-1987	05:02	102	54.3912	165.4893
6.4	08-May-1987	07:18	102	54.3918	165.4893
31.5	09-May-1987	03:27	146	54.7840	165.2562
31.6	09-May-1987	06:01	125	54.9970	165.4843
23.6	09-May-1987	20:12	1990	53.4965	164.0320
31.4	10-May-1987	01:10	112	53.9847	164.4698
31.7	10-May-1987	02:18	89	54.1503	164.4855
23.1	10-May-1987	04:38	97	54.4035	164.3620
30.1	10-May-1987	06:52	103	54.4962	164.0260
31.1	10-May-1987	19:19	66	54.3607	164.6683
31.2	10-May-1987	21:26	60	54.3778	164.8575
21.1	11-May-1987	04:09	975	54.2985	166.4590
21.1	11-May-1987	06:08	1040	54.2950	166.4548
21.1	11-May-1987	20:07	1017	54.2970	166.4617
21.1	11-May-1987	22:34	1024	54.2965	166.4587
21.1	12-May-1987	00:05	1016	54.2962	166.4627